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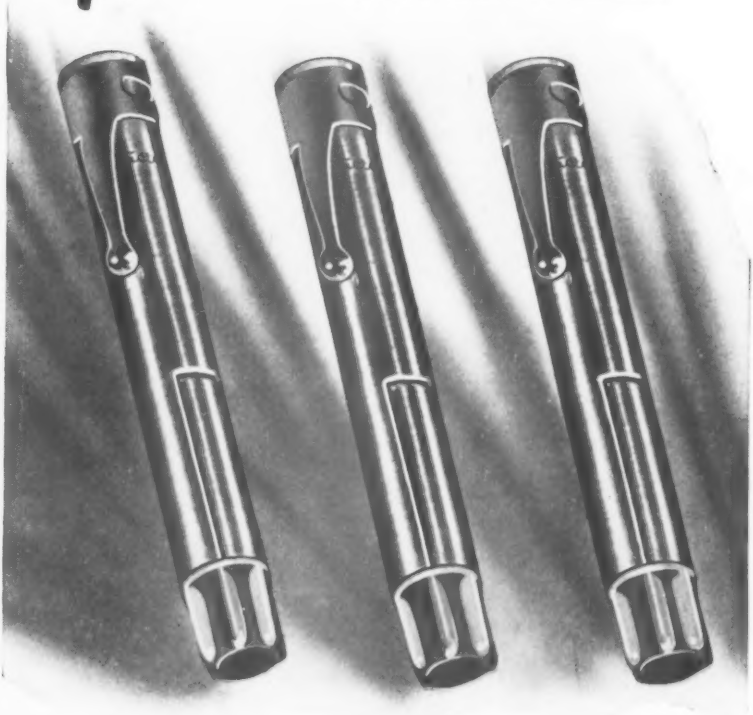

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Vol. 6, No. 5

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The Atomic Industry and Human Ecology

X—SECRECY, WILLY-NILLY

IN OR OUT OF CONTEXT, the content of Professor H. DeW. Smyth's now famous "Atomic Energy for Military Purposes" remains required reading for the informed citizen in this Atomic Age. The book is a mine of information, unfortunately titled however, since an examination of its contents leads logically enough to such erroneous statements as "It is impossible to separate the peaceful from the military uses of atomic energy." If one may reason by analogy here, it is about as absurd to labor the (admitted) fact that radioactivity is useful in war as well as in peace as it is to insist that the entire chemical industry, say, is a war industry because chlorine has been used as a war gas. This example is selected from many because every person knows that chlorine is also used to make water potable if not palatable.

The Smyth Report is outstanding in making readily available to all the people certain bench marks in the omnipresent and growing secrecy-versus-security discussions of the day. It is particularly important because its author in virtue of his present position in the AEC continues to speak on the subject publicly. We are consequently provided a relatively easy way to watch the *trends* and to make our own evaluation of the importance secrecy is beginning to assume in American life. Such a personal evaluation becomes more and more necessary as various authorities deliver contradictory opinions as facts; at such a time men will do well to replace "authority" by reason in the formulation of their own opinions.

It may be that modern man must have secrecy, willy-nilly, but this is by no means certain. *The New York Times* writes editorially, in saluting Lewis L. Strauss as he left the Commission, "The AEC operates for the most part behind a veil of secrecy, for reasons which are obvious and necessary . . . ." NUCLEONICS is pleased to join in the salute; we particularly like Mr. Strauss' insistence on strict interpretation of the law, and agree with him that the best action is to change the law rather than to seek for a different or, as many would phrase it, a more liberal (*sic*) interpretation of the law. But we take strong exception to the now common statement that secrecy is obviously necessary, or that operations must proceed behind a veil of secrecy, for reasons which are obvious.

The most obvious of the many reasons why we cannot agree that secrecy is obviously necessary is illuminated by a story told about most teachers of any great reputation, especially in mathematics and in mathematical physics. For, like the student who asked Professor Jones, "Is the answer to that (partial differential equation) really obvious?," we sincerely do not understand the reasons for the assertion. And we, like the student, are not helped if the

Professor requires to be excused from the classroom and given the balance of the lecture period in his private office before returning to the class with a flat, "Yes. It is obvious."

The trends must be watched. In the Smyth Report we read, "At that time [1939] American-born nuclear physicists were so unaccustomed to the idea of using their science for military purposes that they hardly realized what needed to be done. Consequently, the early efforts both at restricting publication and at getting government support were stimulated largely by a small group of foreign-born physicists . . . ." A "Reference Committee" was later set up in the National Research Council, a non-Governmental agency, and was "organized to control publication policy in all fields of possible military interest." And finally, "It is of interest to note that this whole arrangement was a purely voluntary one; the scientists of the country are to be congratulated (*sic*) on their complete cooperation."

To those who have followed the daily papers, it is clear that if it were to be done over, many scientists would operate without secrecy in the 1939 atmosphere. In 1950 their cooperation is not quite voluntary. Almost all will agree with Oppenheimer in saying, "We know that in secrecy error undetected will flourish and subvert." And to those who might reply that we should get enough scientists on the inside so their errors will be detected, one suggests, in turn, that in the limit all would be inside, so that the great establishment which required so many now has no reason whatever for existence. The rub is that the nonscientists who are now in control of science will continue their mean course. It becomes increasingly clear that secrecy is here to stay and to grow, unless the scientists and others, whose best work cannot be accomplished with it, take positive action to get rid of it. And they may have secrecy, willy-nilly.

Having had an opportunity to observe their fellow scientists' discomfort, life scientists are somewhat better off than physicists, chemists and engineers. Consider the country's great loss had the discovery of aureomycin's ability to spur growth, as reported at recent American Chemical Society meetings, been hidden under the veil of secrecy. Yet it becomes nonsense to say that increased plant growth during war is not a valuable weapon and, if we are to classify all things used in war, then we must either increase the program of secrecy or admit logically that secrecy is not obviously necessary, indeed not necessary at all.

Secrecy has caused a "row" in Congress, more properly a jurisdictional dispute, between the Senate Committee on Armed Services and the Joint Committee on Atomic Energy. Secrecy has delayed the AEC's reactor program, or secrecy prevents a discussion of what has caused the delay. And now as a final blow the Commission has announced a new study to seek an atomic submarine, with General Electric joining Westinghouse in this effort, while "*the Commission indefinitely postponed construction of an atomic plant near West Milton, New York, which was being designed to produce industrial power on an experimental basis.*"

Secrecy, whether we like it or not, is one thing, acceptable if forced on us by circumstances and persons too strong to resist. But secrecy without reason, without an effort by every intelligent man to understand what is or may be necessary, and if accepted without demur, is surely treason.

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GENERAL ELECTRIC

Problems of the Atomic Energy Commission*

This is an age of international tensions. In such an age it has become fashionable to be extreme. It is a fashion which springs basically from the uncertainties and anxieties in the minds of people and from the urge, in times when certitude is gone, to grasp for pat and easy solutions to complex and troublesome problems. It is in this setting, and in the very middle of it, that the AEC must perform its task. Here, one of the commissioners attempts to delineate the major policy problems faced by the AEC.

By GORDON DEAN

Member, United States Atomic Energy Commission
Washington, D. C.

THE PROBLEMS faced by the Atomic Energy Commission can be summarized as below. I have purposely stated them in terms of the two extreme alternative solutions which are frequently held out as the only alternatives.

1 Civilian vs military control of atomic energy.

2 Secrecy to hamper rival development of atomic weapons vs the obligation in the interest of progress with our own program to promote the free flow of scientific knowledge, and in the interest of democracy to keep the people informed.

3 Government monopoly of the atomic energy enterprise vs private industrial control.

4 Whether the Commission shall center its efforts on weapons or on the peacetime uses of atomic energy.

There is hardly a major policy question, or for that matter a minor one, which does not fall within one of these four problem areas. Furthermore, there is not, in my opinion, a decent answer to be found to any of them by taking either of the extreme positions on any of these issues. The only area in which any degree of extremity would be justified is on the comparatively sharp issue of civilian vs military control. Even here, with the principle of civilian control having been decided, certain balances were added.

Civilian vs Military Control

The act which established the Atomic Energy Commission in 1946 embodied for the most part the principles advocated by the exponents of civilian control. The result is a Commission of five civilians. The legislators, however,

* Based on a talk given at Duke University, Durham, N. C., March 15, 1950.

recognized the importance of a very close relationship between the military establishment and the Commission, and there was embodied in the law provision for a branch of the Commission staff under the director of military application, having a primary concern with weapons development. It was provided that this director be a member of the armed forces. There was also embodied in the law a provision for a military liaison committee. Under the act the Commission is required to advise and consult with this committee on all atomic energy matters of concern to national defense, and the military liaison committee is required to keep the Commission fully informed on all atomic energy activities of the defense establishment. The relations thus set up have been increasingly effective and increasingly harmonious.

Secrecy

One of the most troublesome fields for the Commission is the matter of striking a balance between secrecy on the one hand and the free flow of scientific information on the other, the balance between information we shall issue generally and what we shall keep within the project. This is not an issue that can be resolved once and for all; this is an issue which the Commission must live with daily and resolve daily in piece-by-piece fashion.

In resolving these information problems, the Commission has posed to it two kinds of puzzles: puzzles of technical progress and puzzles of sound public policy.

The puzzle of technical progress was discussed at some length in the report made by the Joint Committee on Atomic Energy following the investigation last summer. The dilemma described there is whether this nation safeguards its security best by restricting the circulation of technical data to the people in the atomic energy project, or by opening up the circulation of such data so that the skill and the brains and inventiveness of all American science and industry can be put to work at finding technical answers which will speed our development of atomic energy.

The dilemma of course recurs as we consider each piece of technical information developed. Sometimes the staff and the Commissioners conclude that it would be risky to the national security to publish a document generally; sometimes we find that general publication will speed our program more than it could possibly help rival programs.

The puzzle of sound public policy is with us constantly.

The Commission faces quite frankly the danger that, unless the people are kept informed concerning the basic facts and the implications of atomic energy, the Commission and the related agencies of the Government may become so remote as to leave behind the ultimate rulers of our Government, the people themselves. Government is already too complex. The tentacles of its control form such a disorderly web of functional threads that it frequently becomes necessary to establish commissions of experts to study, trace and appraise and, if possible, untangle the threads which have been woven by other commissions of experts. In spite of all of the efforts of the Atomic Energy Commission through semiannual reports, press conferences, releases to the press and numerous speeches, the great mass of citizens is amazingly unaware of the progress of the national atomic energy program and the implications which are involved in any given course of action.

A recent private poll, taken last December, three months after the President had announced an atomic explosion in Russia, revealed that 26% of the persons polled were unaware of the announcement. This sounds absolutely fantastic and yet the poll was taken by extremely competent experts in this

There is No One Secret. . .

. . . which by itself is of overwhelming importance. There is a series of technical judgments that have to be made. None is likely to be clear cut or important by itself. The best thing we can do is to balance advantages of revealing information to our own people against the dangers of giving that information to a potential enemy. In doing so, we must remember that our future strength in military technology cannot depend entirely on work in secret government laboratories. It will certainly depend also on the vitality of our educational program, on the research of innumerable university and industrial laboratories and on the progressiveness of our industrial technology. A policy of exaggerated secrecy would destroy the very strength it was intended to protect.

The indirect effects of our secrecy policy are more subtle and, therefore, more dangerous. I am concerned by the extraordinary exaggeration given to the importance of secrecy in the public mind. We must not accept the false notion that the safety of the country depends on espionage laws, loyalty oaths and FBI investigations and that the more of these you have, the more secure you make the country's future. Some degree of such measures is necessary in certain areas, of course. I have worked in such an area for most of the last ten years so that I believe I know all sides of the problem. I assure you that these measures are evil and enervating for they are against the traditions both of science and of the free society in which we live. Let us keep these police measures to a minimum and not allow panic or politics to extend them to areas where they are not needed. Our future depends on the strength of our free institutions and free men, even including free scientists. In science, in technology, and in political action, we must depend not on negative restrictions, but on positive achievement.

—From a talk by Henry DeW. Smyth, Amherst College, March 23, 1950

business and purported to cover a representative segment of the American population. Consequently, the need for keeping the people informed about atomic energy is great. The obligation to keep them informed is heavy. It may be that some time when our leaders should in an emergency cry out in desperation for public support on some vital matter of the hour, they will be met with an apathetic silence from an uninformed populace. This, of course, would be tragedy. This is one side

On the other side, there are areas within our program which in the interests of national security cannot be made subjects of public discussion, for to make them public accomplishes no particular good but furnishes to unfriendly powers, bent on aggression and hostile to the United States, exceedingly valuable military information.

In the Commission we have a program for declassifying documents which have been previously labeled top secret, secret and confidential. This is a continuing business. Our criteria for declassification must change as the events of the world change. We are being asked, and properly so, by certain segments of American industry why it is that the Commission will not release certain technical know-how to American business, know-how which may be

known to the Russians, as a result of their own efforts or which may have been handed to them on a silver platter by espionage. The question is a fair one and it is one that we wrestle with daily. It is not an easy question to answer. The general standard is that we hold secret those things release of which would substantially prejudice the security of the United States and that we release, and release fast, information in those areas where the prospect of gain outweighs the prospect of harm. Again, one cannot talk intelligently about secrecy in the abstract.

Furthermore, we must appreciate that decisions on these matters are somewhat affected by the state of mind of the official making the determination to release or not to release. There are those people who instinctively rebel against the release of information dealing with official business. Sometimes their instinct is good. But there are also people whose reluctance stems from a conviction that the subject is too complex for the public to understand, from the conviction that the great masses of the people are dumb, or from the fear that in being frank about public affairs a bureaucratic ineptitude of one kind or another will be uncovered. There are others who believe very sincerely and very deeply that there is a strong obligation for public officials to be completely frank with the people.

The really tough situation arises when you take a person of the second type who holds these deep convictions and place him in a government activity such as the Atomic Energy Commission. As for myself, I find that it is a daily struggle for me to reconcile the duty to disclose with the duty to preserve secret information vital to security.

Question of Monopoly

The third troublesome field for the Commission in which striking the balance is an ever present and challenging problem is the question of whether the atomic energy enterprise should continue to remain a government monopoly with all that entails or a field in which private industrial ownership and operation should prevail. Again I put the question in extreme terms simply to illustrate that no extreme answer will suffice.

During the war the Manhattan Engineering District operated the atomic energy program in complete secrecy and with the tightest governmental control.

The act creating the Commission in 1946 also continued the government monopoly. I am convinced that no other course was possible during the war and in 1946. I am equally convinced that most of it must remain a government monopoly today and perhaps for many years to come. The question, however, is "at what rate and at what pace may segments of the program be turned over to American industry?"

When I ask this question I think it is well that we should have in mind the fact that the operations of the atomic energy program are today carried on under a series of contracts between the Commission and American industry. Our entire physical plant has been built by American industry, albeit with Uncle Sam's dollars, and with minor exceptions all of our installations are operated by nongovernmental agencies. Eleven twelfths of the personnel in the program, while paid by Uncle Sam, are nevertheless employees of contractors. Industry, therefore, is in a very real sense not only participating in the atomic energy program today but running it. But, the problems arise from the fact that the participation is not normal, nor is it equitable, and it is surrounded by numerous restrictions, not simply legal, but restrictions arising from the very nature of our program.

There is, for example, virtually no private risk capital being employed in the field of atomic energy today. This

is not normal industrial participation.

I mention inequitability. This results from the fact that certain industrial concerns which are in the program as prime contractors have an advantage over those concerns which do not happen to be contractors. This means that certain large companies (and believe me we welcome them) are today securing certain technical know-how while other industrial concerns are somewhat in the dark, having access only to scientific facts and industrial know-how that is not classified. Since the materials in which we deal are in large part classified materials and since our business is in large part the making of secret weapons, it is not a field in which there is competition—and for this we pay a price. This cannot be changed over night or in the present state of world affairs.

There are only two fields in which the Commission sees any great future for peacetime applications.

One is in the field of radioactive isotopes for use in the fields of biology, medicine, the study of plant and animal life and in industrial research. It is quite conceivable that a good portion of this program may within the next few years lend itself to private industrial operation. I am certainly not convinced that it need remain a government monopoly.

In the field, however, of atomic energy for the production of power the problems are much more complex. In the first place, the general technical opinion is that it will be ten or twenty years before we are producing electric power from atomic piles on an economical basis. In the meantime we are bending considerable effort toward training physicists and engineers in reactor technology so that there will be a reservoir of competent personnel when the day of atomic power arrives.

We are also bending efforts to acquaint industry through classes, inspection trips and literature with the extent of our program and rate of progress.

There is no prospect in the near future of lifting the government monopoly over uranium used in the production of fissionable materials. At this stage such a course would be utter folly. But the basic problem goes on daily inside the Commission whether in certain areas of the program to extend the monopoly or to diminish it; how far to encourage private industrial participation and how far to discourage it. And always underlying the solution of these problems is the recognition that there are areas which must remain secret. Here again then is another problem which cannot be resolved by any resort to extremes. One is not simply for monopoly or against it, for industrial participation or against it. It is a matter again, as in the other fields which I have mentioned, of hitting a sensible balance

REFERENCE to the semiannual reports of the AEC and to Commissioner Dean's own speeches elsewhere show that he is abstracting portions of the entire atomic energy program to demonstrate the necessity of balance in viewpoint. "Atomic energy" may, NUCLEONICS is certain, legitimately be applied to include all the areas in which the U. S. Atomic Energy Commission carries on its work. Thus, there are clearly great peacetime applications for various accelerators, for example, which Mr. Dean does not discuss here. "Atomic energy" also refers to the operations required in waste treatment and disposal, decontamination problems, construction for the handling of radioactive materials, etc. It is this broad view on which NUCLEONICS bases its approach to atomic energy.

—The Editor

considering the exigencies of the hour and the prospects for the future.

Weapons vs Peacetime Uses

The fourth area which I should like to mention has to do with the problem of whether the Commission should devote its effort to the promotion of weapons or to the peacetime uses of atomic energy. On this subject there is much misunderstanding. It certainly is not an either/or proposition. About the only way that one can visualize the emphasis between peacetime and wartime uses is to draw a large bar (see illustration). To

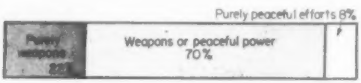

Diagram of apportionment of military and peaceful research done by AEC. Figures shown are very approximate

the right there would be a small white space, perhaps representing five to ten percent of our program, which could be labeled "purely peacetime efforts." On the left there would be a somewhat larger black area which would represent the "purely weapons" end of our program. And in the middle would be approximately 70% of our program which would be represented by a gray space—the area where what we do may in the end yield weapons for war or power for peacetime use. About 70% of the dollars which go into the program today are going into the acquisition of ores, the processing of feed materials and the production of uranium and plutonium metal. It is available for either weapons or peacetime uses. How it shall be used, whether it shall be used for one or the other eventually is not within the power of the Commission to decide.

But one thing I think is quite important to know in talking about peacetime vs wartime uses. The small white section of the bar shown is made up for the most part of expenditures for research. In times of pressure such as we are now going through there will be those who will urge that we give up our basic research in the physical sciences, give up our work on cancer cures, give up our efforts to make progress in the utilization of power from atomic piles. I sincerely hope that such forces will not prevail, for this is exactly what our enemies would like to see.

In this connection, the development of useful power from atomic fission might well be considered for a moment. The military authorities are prodding us all the time to speed the development of atomic reactors that can power a ship or submarine—and well they may. The advantages of such a development are manifest. We respond cheerfully to the goad and are pushing this phase of the reactor program—pushing hard.

But reflect for a moment on the fact that what we learn in this side of reactor development for wartime use may well solve key problems in the development of reactors for central station power—a major boon for the peacetime development of our economy. Likewise, what we learn in the central station power reactor program may solve problems of nuclear propulsion of ships. This reactor development program is one which serves both our purposes—defense and an expanding economy. It is highly typical of that gray area on the bar chart. Our director for reactor development is fond of pointing out that the Diesel engine would not have been developed nearly so rapidly save for the fact that it was useful in driving submarines.

When I speak of the need for balance and for the middle road between extremes I do not mean thereby to give blessing to those who would straddle the fence. The decisions must be made. There can be no straddling. A fence straddler is one who does not decide. What I suggest is that the decisions be balanced decisions.

Design and Construction of a Small Radioactivity Laboratory

It is cheaper to revamp an old building than to build a new one when a small radioisotope laboratory is needed. In this practical paper, the authors describe how they set up a laboratory for general purpose work on a limited budget. The ideas presented can be applied to erection of a laboratory for basic research, hospitals and industry.

By LUTHER E. PREUSS and JOHN H. L. WATSON

Edsel B. Ford Institute for Medical Research
Henry Ford Hospital
Detroit, Michigan

PILE-PRODUCED, radioactive isotopes are available today in quantity and at reasonable cost. This has led a great number of research groups in diverse fields to use them. However, the construction of adequate facilities at a reasonable expenditure presents a serious problem, particularly to smaller institutions. The newness of the field, with consequent lack of trained personnel, adequate equipment and laboratory procedures, has accentuated the difficulties.

The small group in this department designed recently, on a limited budget, a laboratory for radioactivity studies. Since an existing building was revamped rather than a new structure erected, such a procedure will be described in this article. Of course, the same considerations concerning proper construction hold in either case. The installation built here can be used for a wide range of isotope activities and is applicable to industrial as well as medical and fundamental uses.

The problems confronted by this department in development of the laboratory are similar to those of most organizations attempting to adapt their facilities to radioisotope work. In essence, the problem faced was to design, develop and put into operation a suite of rooms adaptable to the following: (1) the general needs of this department, which are those of pure physics research, particularly in problems involving emanations from radioactive materials and their effect on matter; (2) to meet the needs of the institute from a radioactive material supply standpoint and particularly to supply a biochemistry and biology department; and (3) to fill the needs of a large, hospital staff in all stages of tracer and therapeutic work involving isotopes, particularly I^{131} and P^{32}.

The first step was to discover from the people involved some idea of the scope of their proposed work. Two facts of particular note were discovered from these interviews: (1) that every group had problems upon which they were eager to use the isotopic tool, and (2) that with few exceptions the prospective users were vague regarding the quantities and the activity levels which they proposed using.

It was obvious, however, that the type of application would be diverse,

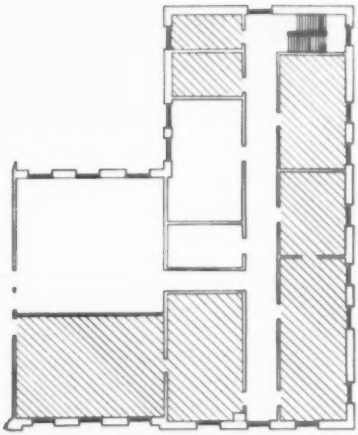

FIG. 1. BEFORE remodeling. Clear area shows space available for the laboratories

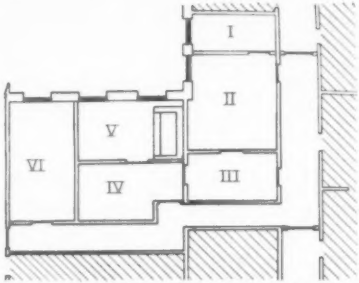

FIG. 2. AFTER remodeling. Plan as revised for the radioisotope laboratory. Note bounding corridor, hood shield in room V and buffer room, VI

and consequently, the laboratories were designed with fairly wide latitude given to space, shielding, methods of decontamination and personnel accommodation. Monetary considerations, however, limit the extent to which this ideal may be realized. The design was such (*1*) that work could be done at activities from below the ten microcurie level up into the millicurie range. Design features all hinge upon the source character and activity levels (*2*).

LAYOUT

The age and condition of the building as well as the particular construction characteristics of the section where the laboratory is to be set up should be studied carefully from the point of view of suitability for the project. Since local building codes and city building laws or restrictions are liable to be counter to best principles of isotope laboratory construction (*3*), the proper authorities should be contacted ahead of time with regard to them. For these reasons the construction and design should be supervised by both a physicist and an architect working closely (*4*).

Building Description

The space which was rebuilt is shown uncrosshatched in Fig. 1. It is located on the second floor of a three-story brick structure of reinforced concrete construction. The floors are of 14-inch solid concrete girders, separated by 7-inch hollow tile forms, covered by approximately five inches of concrete. Sub-girders are supported by main girders roughly 18 inches on a side in cross section. This particular constructional design is common and produces a floor which takes a stress of approximately 500 pounds per square foot. It is ideal for reasons of structural strength and shielding. A hood which is to shield millicurie levels of activity might well weigh many hundreds of pounds and requires a sturdy foundation.

Interior walls were originally of conventional tile and plaster construction and offered little structural strength or shielding properties. Floor and wall

Dimensions of Rooms*

Room	*Length ft in.*	*Width ft in.*
I (Counting)	12–0	6–4
II (Low Activity)	13–11	12–0
III (Monitoring)	12–0	7–0
IV (Intermediate)	14–8	9–9
V (High activity)	14–8	8–11
Corridor	.....	4–11

* The counting, monitoring, and hot rooms are minimum in size and, although they may be changed in shape and juxtaposition, our experience argues against reducing floor areas in these three rooms.

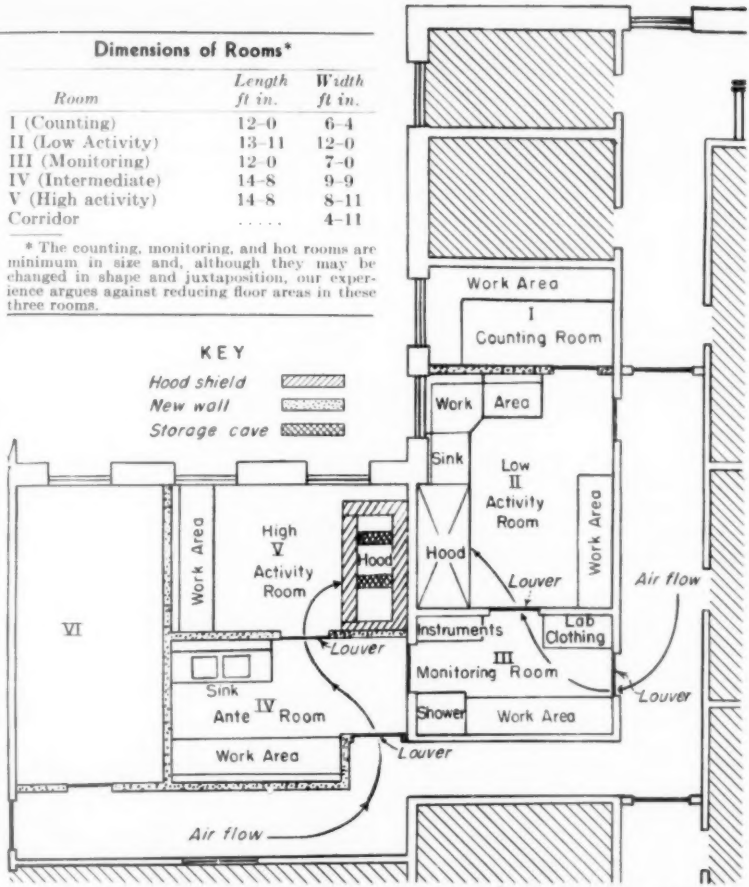

FIG. 3. DETAIL of section showing hoods, furniture and circulation of air

surfaces were painted with ordinary interior paints.

The revised floor plan is shown in Fig. 2. Five work rooms have been made up from the moderate area available (slightly under 600 sq ft). A corresponding area should be available to any group contemplating such a development.

This floor space was chosen primarily because it was not situated directly above a kitchen area, and consequently it was not necessary to run disposal lines through the kitchen. Not everyone will have this serious contamination problem to contend with, but the discussion here is illustrative of ingestion possibilities which did arise and which might arise elsewhere.

The area originally occupied by three rooms has been converted to six, with a bounding corridor. The corridor and

room VI (see Fig. 3) serve as an effective quarantine for non-radioactive work detailed to other sections of the floor.

Monitoring Room

The monitoring room, III, is the key room for the suite. Its placement is analogous to that of an "air lock," and all commerce must pass through it. The other rooms of the section also have doors to the hall for emergency and service use, but these are secured during routine operation and the laboratory as a whole is accessible to the hall only through the monitoring room. All detecting equipment, changes of clothing, surveying and monitoring are centered in this room, and health physics practices are concentrated in and operated from it.

The monitoring room is common to the high-activity section, rooms IV and V, where the activity levels range into the millicurie realm, and to the very low-activity section, rooms I and II, where activities are two or three orders of magnitude below microcurie amounts. Contamination from the high to the low-activity rooms is consistently controlled by careful monitoring procedures required in passage through room III. More than one room is often allotted to health physics in a large installation, but, where space is at a premium, a small but carefully planned section of connecting hallway is sufficient for a monitoring area.

Low-Activity Room

Room II, Fig. 3, is immediately adjacent to the monitoring room and is designed for minute levels of activity such as are encountered in tracer studies and radioautograph preparations. Source strengths well below the microcurie value are encountered in this section, and such a low-activity room might not be required in smaller installations. Work with low activities, which ordinarily is time-consuming, is isolated in our layout from the very high activities found in room V; consequently, exposure of working personnel is effectively reduced.

Counting Room

A counting room, I, is directly incorporated into the laboratory, but a more elaborate installation might permit the area designated for quantitative work to be more isolated from the processing rooms than was possible here. Isolation of quantitative work is a good general rule to follow when space is available. Air contamination, dust deposits and small spills may affect the background to such an extent that the counting room becomes useless. The best insurance against this situation is the enforcement of a thorough set of conduct regulations within the laboratory. The location of the monitoring room itself is a barrier to contamination.

The design here is suitable because the partitioning wall which separates the counting room from the low-activity room is of solid 4-inch concrete block which offers some shielding protection. In addition, the extremely low levels of activity used in the adjoining room do not increase the background appreciably. Some local shielding may still be necessary in certain cases. This may be achieved conveniently by use of cement block or lead sheet.

The counting room contains extensive electronic equipment, such as scalers, electroscopes, amplifiers, etc. If humidity becomes a problem, it may be mandatory to air-condition this room; consequently, it is advisable to keep it small and compact, convenient and easy to maintain. Numerous electrical outlets must be provided, with a number of 15-ampere circuits. Voltage drops, surges and heavily loaded circuits must be avoided.

Intermediate Room

Room IV, the first room adjoining the monitoring room in the high-activity section of the laboratory, is loosely termed the intermediate room. Its function is to serve as an anteroom for room V. It may be used for storage, service, or decontaminating operations. Where the emphasis is of a biological nature, this room is useful for animal treatment and storage, or for ambulatory patient treatment in the case of therapeutic or tracer studies in hospital work (*5*). Lack of floor space in some laboratories may make it necessary for this room to be omitted, but it is well to remember that it can also be important in reducing the contamination from the high to the low sections.

High-Activity Room

From a radioactivity standpoint the most important room in the suite is V, which adjoins IV and backs up against the low-activity room. The isolation of this room is apparent from Fig. 3. It is accessible only by means of its anteroom. Facilities are not elaborate. The hood occupies one side of the room, with a simple laboratory bench on the opposite wall.

The additional shielding required by the hood in this room is an important part of its design (details of hood design discussed on p. 19). This shielding is made up of solid concrete blocks 8 in. × 10 in. × 14 in., or hollow block may be used with the hollow sections filled with concrete. The concrete blocks, which serve as combination base and shield, extend on all four sides beneath the hood, with the latter suspended on the back and sides by a ledge which projects from the block construction. The front of the hood rests directly on the block wall. Eleven, one-half inch openings must be made in this front portion of the block wall to accommodate the remote controls. On the sides and back the shielding (*6*) stands $5\frac{1}{2}$ feet high, whereas in the front it is erected only to the working apron of the hood. The higher portions of the shield reduce background in the other rooms, while the operator is shielded by lead brick on the apron. No additional shielding was needed on the floor under the hood or in the ceiling above it. The inverse square law and the heavy concrete structure reduce radiation beyond these surfaces to a safe value.

The fitting of unitized furniture into the laboratory is a critical consideration which must be applied to the dimensioning of all of the rooms. A careful study of the size and shape of the individual units must be made beforehand. If a wall is out of position by as little as $\frac{1}{4}$ in. it may be necessary to omit an important piece of furniture.

SPECIFICATIONS

Certain basic criteria exist regarding building methods and materials for a radioisotope laboratory (*7*, *8*). These arise from the need for easy decontamination of floor, walls and fixtures, and from the shielding requirements. This is of particular importance in the "hot" section. Special precautions must be used to cover all concrete and raw plaster areas, and dust collectors, such as overhanging pipes, should be eliminated. Paints must be nonporous with a hard-finish surface. Fixtures and facilities of simple design which lend themselves to easy decontamination are most desirable. Provisions for storage and disposal of waste are required. These and many other needs underline the necessity for careful planning and execution of the plans.

Flooring

Tile flooring* was installed throughout the laboratory. Cracks between

* Armstrong's No. 318, $\frac{3}{16}$ in. × 9 in. × 9 in. asphalt tile with 4-in. cover base, Armstrong Cork Company, Lancaster, Pa.

FIG. 4. Wall construction showing the cement block with furring in place. Wall board masonite was installed over furring

FIG. 5. Intermediate room showing wall finish

squares are quickly closed after brief usage, but admittedly these fissures may be a definite contamination hazard. This danger is discounted by the ease of replacement in the event some squares become fouled by a radioactive spill. In this latter respect small squares of tile are superior to large sheets of linoleum. The 4-in. asphalt baseboard used on the wall with the tile is important. It fills the crack between tile and wall very effectively and is an aid in washing the floors.

Wall Construction

In the process of partitioning off the isotope section, it was necessary to erect four walls, Fig. 2. Three types of wall construction of similar cost were immediately available: chalk block, hollow cement block, and solid cement block. Solid cement block, dimensions of which were $8 \times 12 \times 4$ in., was chosen (*4*). This choice was made more because of the extra space the narrow, solid blocks afforded than because of their inherently greater shielding capacity. The principle of massive, distant shielding was always discouraged with the preference given to small shields close to radiation (*6*) sources. This practice eliminated the excessive cost of heavy walls and lead-lined rooms.

Wall Surfacing (*9*)

Of the several conventional finished wall surfaces available, it was decided that hard-surfaced masonite sheeting laid over $\frac{1}{2} \times 2$-in. furring was most desirable. This type of covering is superior to plaster or other porous materials, since accidental spills will not easily soak through it into the wall proper. If the masonite does become contaminated, it is an economical and simple procedure to replace the standard 4-ft sections. Figures 4 and 5 show before and after views of this construction, which was installed in rooms IV and V. It was not necessary to use this surfacing in the remainder of the rooms since the expected levels of activity there were low and the chances of contamination slight. Cracks between masonite sheets are covered with $\frac{1}{4} \times 2$-in. wood strips or with one of the available commercial tapes.

Lighting

In the case of this laboratory, fluorescent lighting fixtures of a simple design were specified for the ceiling. They are of a flush mounting type (*4*), which have no horizontal surfaces for dust collection.

Ventilation

The layout and construction for the various doors in the laboratory is another vital factor in the design. A

hood for radioactivity work should have a linear air flow of roughly 100 ft per minute (80–90 ft per minute may be optimum). If a hypothetical case of a hood with window space of 10 sq ft is considered, this means that a blower is needed which will displace 1,000 cu ft of air per minute. Most hoods have a window opening of at least 10–15 sq ft. Unless a free air supply of 1,000–1,500 cu ft per minute is at hand, a slight evacuation of the laboratory will occur and the linear air flow will decrease to a dangerously low value at the hood opening.

To obviate this difficulty, louvers were placed in four of the doors. The positioning of these louvers may be seen in Fig. 3. It will be noted that the high-activity section has an air supply independent of the low activity area (4). Figure 6 shows one of the doors with the louvers installed. This air flow may be disrupted by incautious use of the interconnecting doorway. Stringent regulations may obviate this, or adjustable louvers can be installed. In any event, air flow from the "hot" section to the low-activity section is to be avoided.

The hazard of contamination via the air is a vital danger. Where the floor plan is compartmented according to room usage, distinct air supplies for each section must be secured.

Heating

The heating is integrally connected with the general problem of ventilation and air supply for the hood. The large volume of air moved by the hoods is an important factor to consider when calculating the capacity of the heating units. It is best for the physicist to collaborate with a heating engineer regarding these factors.

Elaborate and expensive systems of heating have been recommended (4) for some laboratories. Organizations with unlimited resources may integrate radiant heat along with air conditioning and humidity control. Small groups may find this space-consuming in the minimum laboratory and very expensive, especially where the development involves remodeling.

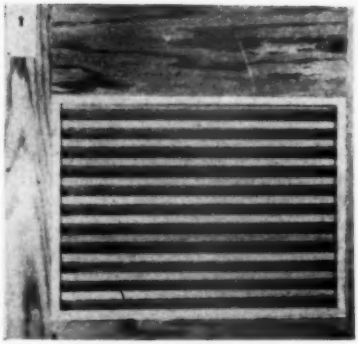

FIG. 6. Simple louver

It was decided that conventional gravity-fed hot water radiators were too bulky, hard to clean, and took up much valuable floor space. Consequently, unit blowers,* which are approximately 1 ft square and 5 in. deep with a metal exterior case covered with hard-surfaced, baked enamel, were prescribed for the various rooms. The advantages are: diminutive size, offering little surface for dust contamination, convenient and efficient source of heat, and operation either on hot water or steam. The large capacity of the hoods and the problem of circulation of air demand careful consideration in the placement of the blowers.

Utilities

An adequate supply of the usual laboratory facilities is necessary. Room I requires a number of load-free 15-ampere, 110-v a-c circuits. Erratic counting may result from voltage

* Modine Unit Blowers, Modine Manufacturing Company, 1222 State St., Racine, Wis.

fluctuations present on supply lines to scalers, monitoring equipment, or high voltage units for Geiger-Müller tubes. A voltage stabilizing unit* installed in the counting room and designed to feed all possible combinations of instruments eliminates this source of counting error. It is a mistake to limit the number of circuits in even the smallest laboratory counting room where three 15-ampere load-free circuits is an absolute minimum. The monitoring room is supplied with two load-free 15-ampere circuits to supply the ordinary plug-in equipment. A water supply and drain are needed for the emergency shower.

Rooms II and V require complete facilities common to the chemical bench. These include hot and cold water, gas, compressed air, steam with return lines, 110-v a-c, vacuum lines, etc. Each hood is outfitted with a double set of the utilities, and corresponding services are distributed on the work benches.

Room IV requires utilities whose character will depend upon the room function. In the case of our laboratory, gas, air, water and electrical outlets were specified. Drainage lines to handle hot material require special consideration. Because of water contamination, monitoring and safety precautions must be considered at the outset (*10*) with placement of traps and disposal lines a critical matter. For large operations a central collecting trap or traps is useful. Here large volumes may be imprisoned for a number of half-lives, or until dilution takes the activity below the danger point. Such units are large, must be highly accessible, well-shielded, and demand special equipment.

In our design, AEC recommendations (*11*) of disposal of wastes by "dilution and dispersion" were followed rather than a method involving confinement and control. For obvious reasons each sink was supplied with lead traps in preference to the conventional cast iron type. Disposal lines are routed through safe areas and are located for ease of monitoring.

Supply conduit and piping were either buried in the walls or laid close to the ceilings where they might be covered with a false ceiling to eliminate the danger of dust collection.

Painting

The ordinary finishes suggested by the painting department were too porous for use in areas where contamination was a possibility. A hard-surfaced enamel* was specified for the five rooms. The enamel has an impervious skin, and is easily washed and dried. The surface resembles varnish but has a resistance to water not found in non-spar varnishes. Various shades are available to harmonize with the balance of the building interior. Some of the new peelable plastic paints are more highly recommended, but their cost and the necessity for usage of strange techniques in their application precluded their use in these rooms. Two recommended paints are "4-A Plastic Paint"† and "Heat Reactive Varnish F-GV-5293."‡ Also suggested are the following: Prufcoat, Amercoat, Stripper Base, Strippable Surface (*4*).§

Special Problems

Certain problems were emphasized by the nature of the building's over-all design and function. The most vital of these was the proximity of a cafeteria, which serves several hundred meals

* Sorensen Voltage Stabilizers, Sorensen and Co., Inc., 375 Fairfield Ave., Stamford, Conn.

* High Gloss Enamel, #193, Watson Standard Paint Co., Pittsburgh, Pa.
† Interchemical Corporation, Chicago, Ill.
‡ duPont de Nemours & Company, Inc., Wilmington, Del.
§ Leaded paint, Lewis Berger & Sons (British), Australian Branch Plant [NUCLEONICS **5**, No. 1, 81 (1949)].

each day and is located immediately adjoining the area available for the laboratories (Fig. 3). On the floor below, a large kitchen is situated. Since one of the most dangerous aspects of the use of radioisotopes is ingestion of the materials, it was immediately apparent that some buffer arrangement was required between the food handling areas and the laboratories.

Another matter encountered in remodeling is the presence of overhead piping and conduit, which will be a source of danger in regard to the collection of radioactive particulate matter. False ceilings of masonite sheeting serve to cover these areas. In an old building such as ours, the positioning of disposal lines and "stacks" demand careful study. Ideally, they should be easily available for monitoring and yet removed from danger areas, such as the refectory.

A layout problem was presented by the fact that the area proposed for remodeling was used by non-scientific personnel. Although this traffic could be minimized by stringent rules, routes which were contamination-free had to be devised. In this respect, it was necessary to reconcile the layout with local fire rulings, which demand free access to the halls for all personnel. Fortunately, space was available for a bounding corridor, but where space is not available, prohibitions on traffic may be set down in the isotope laboratory regulations.

FURNITURE

Modular Units

The general layout of the furniture as used in the isotope suite is shown in Fig. 3. Work with radioactivity places rather demanding requirements upon furniture. It must be adaptable to various rooms and room dimensions, easily cleaned, simple in design with smooth, hard, working surfaces, which are not easily contaminated.

Although the furniture chosen* does not completely answer all of the needs for radioisotope work, it comes close to filling these requirements. The top of high polish, stainless steel is a factor in the choice, since it allows for easy decontamination. The bases of the units are all metal with a hard, baked-on enamel, providing easy cleaning. The small cracks which exist between adjoining units are ordinarily filled up with a nonhardening polymer, but this was not advisable since it was a collector of dust, *etc.* The units were joined by special, stainless steel, soft solder (high tin content), fluxed with Allen's acid.

For some applications 30-in. high benches are preferable to 36 in. ones. A good general rule to follow is to install the 36-in. units where chemistry is to be done or where operations are carried on with the researcher standing. However, when tall apparatus is to be used, or when it is necessary to look down into the work, 30-in. heights are preferable.

Clothing Storage

Two small closet-type units† are installed in the monitoring room for storage of laboratory gowns and coveralls. This location allows for convenient monitoring procedures. Clothing to be laundered is also kept here. The smaller of the two cabinets stores such articles as rubber gloves, absorbent paper for spills, *etc.*

Hoods

It is not possible to purchase from commercial sources all of the special furniture and laboratory installations which must be built into a radioactivity laboratory. Chemical hoods are one such item. Hoods may fall into two general categories: (1) the specialized type designed for a specific piece of

* A. S. Aloe Company, St. Louis, Mo.
† All Steel Equipment Company, Aurora, Ill.

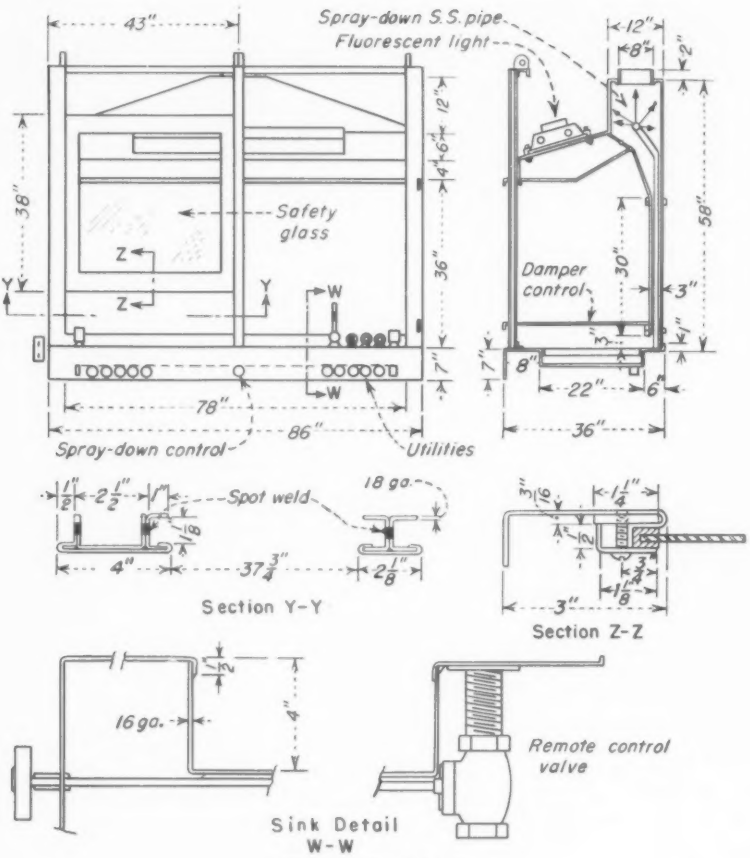

FIG. 7. Hood detail

work, *i.e.*, handling of C^{14} or a microchemical process (*12*); and (2) a hood intended for general-purpose work.

Most of the routine work in such a laboratory centers about the hood, and it requires certain special features. It must be easily washed and decontaminated and should be virtually leakproof. The material from which it is constructed should be either easily cleaned or inexpensive enough for entire replacement after extensive contamination. The blower must be extremely reliable. Washdown facilities are a necessity, and more elaborate baffling than is ordinarily found must be provided. The foregoing is a very brief enumeration of the basic design requirements (*9, 13, 14, 15*).

At first, no commercial hood was available which would fulfill a majority of these requirements, and it was necessary that one be custom designed and constructed. Two were made,* one to

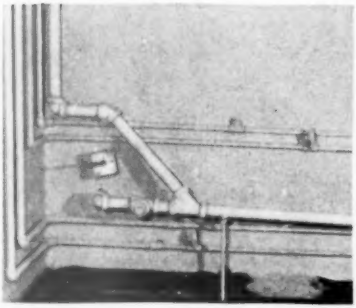

FIG. 8. Utilities necessary for hood installation. This piping must be integrated with shielding

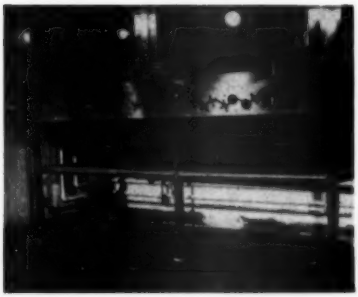

FIG. 9. Method of support for the low activity hood. Pipe standard is covered with a masonite front for prevention of dust accumulation

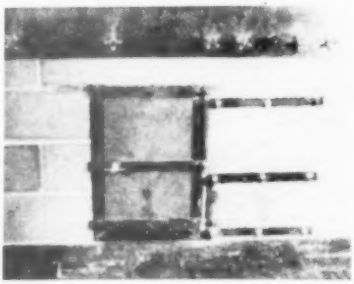

FIG. 10. Concrete shield also acts as base of hood, room V; storage cave in base can be seen

FIG. 11. Partially completed shielding for "hot" hood

be positioned on heavy shielding in room V, and the other with little shielding in room II.

Figure 7 shows the working blueprints from which the hoods were made. Figure 8 shows the piping necessary for hood installation. Construction is of stainless steel throughout with a No. 4 satin finish on all surfaces liable to contamination. Remote control facilities are provided.† Utilities positioned on the exterior are often preferable to the design shown here.

The hoods themselves are built without base or other internal shielding provisions. This feature allows for a wide range of uses either in low or high-activity work. The hood may be placed on a pipe standard as was done in room II, Fig. 9, or upon a concrete shield as in room V, shown in Fig. 10. Partial construction of this concrete block foundation-shield is illustrated in Fig. 11. It is so designed that standard, solid $8 \times 10 \times 14$-in. concrete blocks may be used for a foundation. The block is preferable to a poured concrete base since single blocks may be removed if necessary after serious contamination.

The block foundation can serve as a

* Universal Foundry, Detroit, Mich.
† Leonard Peterson and Company, Inc., Chicago, Ill.

storage cave to accommodate a small lead safe for active materials. An opening is provided in the base and is fitted, Fig. 10, with a lead door $1\frac{1}{4}$ in. thick, roughly equivalent to 8 in. of concrete shielding. This door also provides an entrance for a serviceman on occasion. The hood is covered above and below with false masonite, needed particularly with a porous, concrete block foundation.

Much of the work demands some sort of table-like surface within the hood. The design is easily adaptable to the addition of a stainless steel, false floor over half of the sink, from rim to rim, movable from one end of the sink to the other. If bulky equipment is to be used within the hoods, it is often necessary to drop a section of the sink floor.

Hood Venting

Each hood should have its individual blower and ventilating system, and special precautions and inspecting procedures are required in setting these up. Venting on both hoods was carried through the attic and attached there to a 1,500 cfm blower.* Vertical discharge stacks were placed 15 ft apart on the highest portion of the building roof. The tops of the stacks, provided with spinning caps,† which are shown in Fig. 12, are 10 ft above the roof. The building itself is 48 ft high. These caps were installed to ensure that there would be an air flow in the hoods at all times. They turn in the slightest breeze, producing a negative pressure in the hoods, and maintain a minimum of 15 to 20 linear feet per minute air flow with hood windows one-quarter open. There are no abrupt turns or bends in the venting, and all joints are carefully joined and soldered in such a way that no cracks or apertures of any

FIG. 12. Hood stacks, showing method of bringing vent through roof

type exist in the system. Where extremely corrosive gases will be vented by the system, a commercially available, non-metallic flue is advisable.

Since even the best blowers are inclined to vibrate and to produce cracking in near-by fittings if direct couplings between stack and blower are made, heavy, flexible asbestos cloth collars were used on the two connections at each blower. These are made leakproof with a semi-plastic caulking to preserve the flexibility of the collar. They need periodic monitoring (*16*).

The venturi effect will, in general, maintain a negative pressure differential within flues below the blowers. Above the blowers some positive pressure may develop, especially in the case of the stacks equipped with a spinning cap.

A second connection of particular interest is the point of passage of the stack through the roof of the building. The details may be seen in Fig. 12. The stack is not joined to the roof except by the three guy wires. A small

* Utility Blower, 2,000 cfm, $\frac{3}{4}$ H.P., 3-phase, 220-v a-c, American Blower Co., Detroit, Mich.
† 18-in., Type C, Allen Turbine Ventilator, Allen Ventilating Equipment, Rochester, Mich.

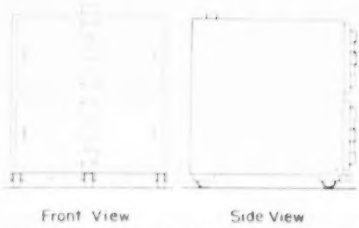

FIG. 13. Lead safe for isotope storage under high-activity hood. Stack is used for ventilation through hood

cone at the base of the stack stops moisture from entering the attic. With this type of opening, it is not possible for vibration to rupture the stack at the point where it passes through the roof. Another desirable result effected by this type of venting is the lack of vibration in the laboratories directly below the installation.

The heavy blowers and motors must be mounted to minimize noise and vibration. Excellent results were obtained with a floating platform on a swinging suspension hung from the building rafters and shock mounted with foam rubber and springs. The motors are remotely controlled by switches positioned near each hood. Filters for air from the hoods can be selected to engage the specific particulate material anticipated. Installation should be in an easily accessible region. When the venting installation is completed and in operation, then it will be necessary to set up checks (*17*) on the operation of this disposal system, especially if relatively tall buildings are located near the stacks.

FIG. 14. Hood in operation. Remote controls are visible below lead brick shield

Storage

For the storage of moderate amounts of isotopic material, this laboratory has found that the cave beneath the high-activity hood is satisfactory. In larger installations, a separate room devoted to storage purposes will be necessary. A small lead safe on wheels may be rolled into the storage cave. Reproduction of the working blueprint for the safe is shown in Fig. 13. Individual doors may be used to obviate the necessity of exposure to the entire quantity of active material when removing part of it. The top of the safe requires extra shielding (*17*) to reduce the radiation escaping via the unprotected hood sink.

From the shielding table data prepared by C. C. Gamertsfelder (*19*), assuming that 500 millicuries emitting 2-Mev gammas are to be stored, it is found that at one meter from the safe the minimum amount of concrete shielding is 30 cm or 11.6 in. for an operator's eight-hour day. In room V there are eight inches of concrete, plus one inch of lead in the safe, which gives an equivalent thickness in excess of the required amount.

INSTRUMENTATION

Custom Units

Some of the purely medical applications in this laboratory have necessitated the construction of a vehicle suitable for safely transporting the scalers and other instruments and material to distant rooms.

Lead bricks (*20*) of a special tongue and groove design were developed in

FIG. 15. Left to Right: Monitoring bench in room III; work area in room V set up for dilutions at intermediate activity levels; basic measuring instruments on counting room work bench

these laboratories, because, at the time, none were available commercially which eliminated simultaneously the faults of tipping and radiation leakage. A protective wall constructed of these bricks is shown in Fig. 14.

Although some are commercially available, it will be necessary to design and construct special devices (*21*) for remote control work.

Apparatus

The scope of the proposed work and the budget figures will determine the extent of instrumentation (*22*). It is generally agreed that a *minimum* amount of work in the field demands a total budget of about $10,000 a year, including salaries of personnel.

Probably in no other field are there so many applications for special instrumentation, *e.g.*, with microchemical devices (*12*) and electronic instruments.

A minimum selection of the various isotope laboratory tools is listed below in relative order of importance (*23*).

1. Two devices are required for **monitoring** purposes: first, an easily portable instrument reading in milliroentgens per hour and preferably also in counts per minute for surveying in all parts of the suite of rooms; secondly, a counting-rate meter situated in the monitoring room, line operated, to check all commerce through the laboratory.

2. **Health physics** devices are needed. AEC recommendations specify a film badge, two pocket chambers, and finger ring badges for each worker. If local calibrations are to be done, photographic laboratory facilities and chargers for the chambers are required.

3. **Measuring devices** and **standards** are used for detecting source strength; varying combinations of scalers, G-M tubes, ionization chambers, proportional counters, electrometers and electroscopes are needed.

4. **Remote control** tools, including tongs, special glassware, shielding, etc., are almost always required (*24*).

5. **Standard laboratory supplies** include the usual glassware, balances, burners, etc., some of which need modification for the work.

Some of the equipment may be constructed by the laboratory; much is commercially available. The Atomic Energy Commission* has available design blueprints of many special purpose devices.

Figure 15 shows equipment in use in the monitoring, high-activity and counting rooms.

LABORATORY ORGANIZATION

Steering Groups

When the laboratory reaches the final stages of completion, it becomes necessary to set up the organization (*25*) which will guide the various sections' activities. Suggested advisory and ruling bodies which have been

* A particularly helpful publication is the "Radiation Instrument Catalog," Technical Information Branch, AEC, Oak Ridge, Tenn.

found useful here are made up as follows:

Research Committee

This committee, with the local department head as chairman, ranks first in importance among the steering committees. Its function as an executive body is to administer the laboratory, rule on proposed work and determine its worth and feasibility. The chairman may call in as advisors other department heads or the isotope laboratory supervisor.

Local Isotope Committee

The isotope committee is formed, in our case, to handle those affairs particularly related to human applications. This group is expressly required by the AEC* where human work is to be done.

The composition of this body is:

1. A physician trained in internal medicine.
2. A physician trained in hematology.
3. An individual experienced in assay of radioactive materials and protection of personnel against ionizing radiation.
4. A qualified physicist and therapeutic radiologist.

Rules Committee

The function of this body is to compile and enforce a comprehensive set of rules, designed for a specific laboratory and project.

Health Physics Group

This sub-group, functioning with the rules committee, is set up to ascertain radiation levels and to supervise and carry out precautions in regard to radiation hazards (*26*).

Records

Some paper work is necessary from a routine standpoint, and certain aspects demand special files and records. Legal eventualities are especially important in considerations of health physics records of personnel and dispensation of the radioactive material where human treatment is carried on. The destination and usage of various shipments should be cataloged and certified by the laboratory supervisor.

The monitoring records should be certified periodically by a qualified person (health physicist) and kept available for reference. Dosage data from daily chamber, weekly badge and weekly film ring meters are entered in an orderly fashion and preferably recorded on a special form for this purpose. The long-range studies of small exposures can only be made if all laboratories, large and small, carry out this vital work. Because of poor statistics, this type of radiation exposure is one of the unknowns in working with radiation (*23*).

Isotope procurement files again demand certification. A special form is recommended. Usage and depletion columns are especially important. The supervisor's initials must certify each entry on the completed page.

Highly recommended by the AEC Isotopes Division, Advisory Field Service Branch, is a record on radioactive waste disposal. Found useful in our record system, it is especially good when integrated with the procurement and depletion forms. It is mandatory for routine operation as well as good insurance against litigation.

Data book entries on calibrations and on measurement should correspond with the values given in these files.

Blood counts are highly recommended by the AEC, and these counts taken periodically must be part of the health physics files.

Instrument records in some cases are useful, especially where a large number of units are in use. Logs of operating time are useful in anticipating trouble.

Personnel morale is always a problem

* Page 30, "Isotopes, Catalog and Price List No. 3," (Isotopes Division, AEC, Oak Ridge, Tenn., July, 1949).

in this work, and is considerably bettered by close administrative attention to health physics.

SPECIAL SERVICES

Certain maintenance problems are unique in this type of laboratory, and a system might preferably be set up at the onset of operations. It is very important at times that the hoods be continuously operated. This means periodic checks and oiling of the blowers and spinning caps. Janitor service must be supervised to some extent and the individuals carefully instructed in their particularly duties.

Monitoring routines must be established, hood venting inspected periodically, sink traps and disposal lines checked, and dangerous dust deposits cleaned.

Laundry service at times can present a problem and demands special handling.

CONCLUSION

From a financial standpoint the remodeling of a building for radioisotope use may seem at first glance a sound thing to do when compared with the initial cost of a new building. From our experience, this seems to be a good rule to follow, if the development is small. However, when the project becomes large, it is wise and economically feasible to consider construction of a new structure.

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RANDOM SAMPLING (Monte Carlo) TECHNIQUES in Neutron Attenuation Problems—I*

Only a slight knowledge of statistics is required to understand this discussion of a simplified method of making complex calculations without advanced calculating machines.

By HERMAN KAHN

The Rand Corporation
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By applying random sampling techniques to the problem of neutron and gamma ray attenuation in thick shields, deductions about the behavior of a large number of neutrons are made from a study of comparatively few.† The technique is quite analogous to public opinion polling of a small sample to obtain information concerning the population of the entire country.

Use of random sampling to solve a mathematical problem can be characterized for many applications as follows. A game of chance is played in which the probability of success P is a number whose value is desired. If the game is played N times with r wins and $N - r$ losses, then r/N is an estimate of P. The game of chance to be played may be the direct analogy of the physical or mathematical problem to be solved, or it may have little apparent connection with the problem of interest, other than that both give the same answer.

In order to play a game of chance, a gambling device such as a roulette wheel, dice, or coins must be available. The simplest and most practical gambling device from the viewpoint of the computer is a table of random numbers. Such a table usually consists of the digits 0 to 9 arranged so that the probability that the nth entry is x is 0.1 and so that every entry is statistically independent of the other entries. By using this table it is possible to select a random equidistributed point on the line 0 to 1 to any desired degree of accuracy by combining the digits in the form $0.xyz$.

As an example of a simple game whose probability of success P is the answer to a mathematical problem, consider the evaluation of the integral

$$J = \int_0^1 g(x)dx \qquad 0 \leq g(x) \leq 1 \quad (1)$$

by random sampling. The rules of the game are as follows:

1. The numbers ω and ρ are selected at random from a population equidistributed in the range 0 to 1 (to as many significant places as necessary).

2. If ω is less than $g(\rho)$, the game is a success; otherwise it is a failure.

As can be seen from Fig. 1, the probability of success is just equal to the area under $g(\rho)$ or J. So an estimate of J is given by r/N where N is the total number of trials and r the

* Copyright 1949., The Rand Corporation, Santa Monica, California.

† The original suggestion to work neutron problems in this way came from J. von Neumann and S. Ulam. Although many other people have worked in the field, including H. Bethe, W. DeMarcus, R. Echols, U. Fano, T. E. Harris, A. S. Householder, G. Goertzel, H. Kahn, N. Metropolis, L. A. Ohlinger, R. D. Richtmyer, and S. W. W. Shor, there has been almost nothing published, and much of the general field remains to be explored.

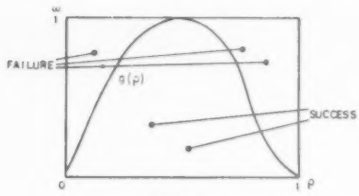

FIG. 1.

number of successes. The probable error of the estimate* is

$$0.6745\sqrt{\frac{J(1-J)}{N}}$$

The technique just described would not ordinarily be used in the evaluation of a one-dimensional integral, where the standard numerical methods are far superior. The advantages of the stochastic method become apparent only in the evaluation of a multidimensional integral. If N points are needed to evaluate a one-dimensional integral to a certain degree of error by a stochastic technique, it will still take only N points to evaluate a "similar" k-dimensional integral as accurately. If the same problems were done by numerical integration, and if it took n points for the one-dimensional integral, then it would take about n^k points for the k-dimensional integral (because each one of the k axes must be divided into n parts). As soon as $n^k > N$, it therefore becomes efficient to use random sampling. In practice the dividing line seems to be about $k = 4$ or 5.

In the problem of interest—the transmission of particles through thick shields—it is possible to calculate the probability P for this transmission by a series of the form $P = \sum_{n=0}^{\infty} P_n$, where P_n represents the probability that a particle penetrates the shield with exactly n collisions. Since the calculation of P_n involves a multiple integration of order at least $3n$, it is clear that if the problem is to be treated in any way that is equivalent to calculating the P_n by numerical integration, random sampling should be considered.

RANDOM SAMPLING—AN ANALOG DEVICE

Ordinarily, the use of random sampling in particle transmission studies is approached not through the device of using integrals representing the nth scattered beam, but as a statistical analog of the actual physical situation. To take a simple problem, there are three ways of finding the probability of throwing a seven with a pair of dice. The first is to find the various combinations of two dice that total seven and add their respective probabilities. In the neutron problem, this corresponds to the exact calculation of the probability of each of the n different scattered beams.

The second (experimental) method is to toss pairs of dice a large number of times and determine the proportion of throws in which sevens appear.

The third method is to draw a digit R from the random number table previously described and say that this number represents a throw of a die if it is a 1, 2, 3, 4, 5, or 6. Otherwise it is discarded. Thus, drawing any two numbers is statistically the same as throwing a pair of dice, although a bit faster, because it is easier to pick numbers from a table than to throw dice.

The behavior of neutrons is also governed by probability laws, although in a somewhat more complicated fashion than that of dice. In using statistical methods to trace typical life histories of neutrons, it is necessary to pick values of a random variable. In general, there is given a probability density function $f(x)$ such that $f(x)\Delta x$ is the probability that the random variable lies between x and $x + \Delta x$. There is also given the table of random numbers, R_i, described previously. To select a

*Refer to any discussion on the binomial distribution.

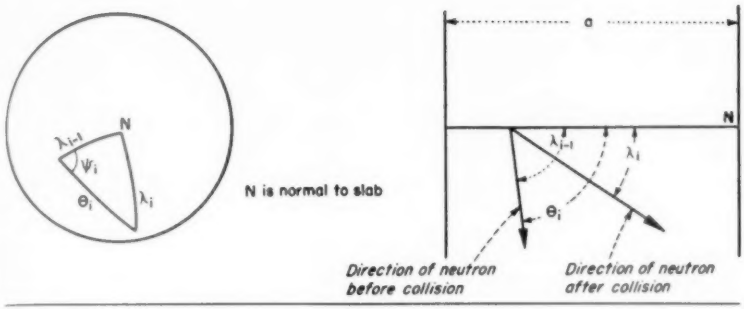

FIG. 2.

value of x at random out of the population described by $f(x)$, a random number is chosen from the table and the following equation is solved for x_i:

$$\int_{-\infty}^{x_i} f(y)dy = R_i \qquad (2)$$

An alternative and sometimes more convenient technique is often used. For simplicity, let $f(x)$ be defined only in the finite interval from 0 to 1, and let M be the maximum value of $f(x)$. Two random numbers, R_1 and R_2, are picked from the table. If $R_2 \leq f(R_1)/M$, then R_1 is the value of x to be used. If $R_2 > f(R_1)/M$, R_1 and R_2 are discarded; two more random numbers are picked and the same procedure is repeated. It is easy to see that both procedures will give a probability that the random variable lies between x and $x + \Delta x$ equal to $f(x)\Delta x$.

A typical problem that might be worked by these techniques is the transmission of neutrons through a plane slab infinite in the y and z directions and of thickness a in the x direction. A beam of neutrons with a prescribed distribution in angle and energy is incident on the left face, and the problem is to calculate what percent penetrates the slab. This is done by random sampling as follows:

1. A neutron is chosen at random out of the initial distribution of angles and energies.* Its energy is denoted by α_0 and its angle with the normal to the slab by λ_0.

2. The point of first collision, x_1, is chosen from the distribution

$$h(x_1) = \frac{\mu_0}{\cos \lambda_0} e^{-\frac{\mu_0 x_1}{\cos \lambda_0}}$$

where μ_0 is the reciprocal of the total mean free path.

3. The type of nucleus involved in the first collision is then chosen at random, according to probabilities determined by the composition of the materials and by the cross sections of each nucleus.

4. The type of collision is chosen next. If the neutron is absorbed, the history is terminated and a new history started. If the neutron is scattered, a new energy is selected from the appropriate distribution.

5. If this scattering is inelastic, the angle of deviation θ_1 is picked from the angular distribution function for inelastic scatterings. If the scattering is elastic, the angle is calculated from the change in energy.

6. A new angle with the normal is now calculated, using the spherical trigonometry formula

$$\cos \lambda_1 = \cos \lambda_0 \cos \theta_1 + \sin \lambda_0 \sin \theta_1 \cos \varphi_1$$

* The technique used to pick a sample value out of a two-dimensional distribution is given after Eq. 10, in the section on numerical integration.

See Fig. 2. The angle φ_1 is the change in azimuth and, if polarization effects are unimportant or neglected, is a random number uniformly distributed from 0 to 2π.

These six steps are repeated until the neutron is absorbed, degraded to a negligible energy, reflected, or transmitted through the slab. If N neutrons are traced and r actually get through, then an estimate of P, the probability of transmission, is r/N. The probable error has the value $0.6745\sqrt{P(1-P)/N}$, and the probable percent error (p.p.e.) has the value $67.45\sqrt{(1-P)/PN}$. Since P is not known, it is replaced by r/N in the calculation of the error.

Problems of this nature and more complicated space- and time-dependent problems have been carried through by the Oak Ridge National Laboratory (A. S. Householder, G. Goertzel), Los Alamos Scientific Laboratory (S. Ulam, N. Metropolis), and the NEPA Project (R. Echols). The actual calculations for NEPA have been done at Northrop Aircraft, Inc., under the supervision of L. A. Ohlinger.

Most of these investigations have been concerned mainly with studying the behavior of typical neutrons. For this problem, the use of random sampling as a straightforward analog of the actual physical situation is fairly satisfactory. The difficulty with using this technique for a shielding problem can be seen by studying the estimate for the p.p.e. For the P's of interest (10^{-6} to 10^{-10}) values of N of the order of 10^9 to 10^{13} are required to obtain the accuracy desired. This is beyond the region of practicability, even for a high-speed computing machine.

It is therefore necessary to replace the sampling and estimation procedure defined by the previous six steps by one which has the same expected value but requires a smaller number of histories to make an accurate estimate. The computer should regard the six steps as defining the mathematical problem and not the sampling procedure. The latter (as will be shown) is to a certain extent arbitrary and should be chosen to minimize the total amount of work rather than to be an analog of the physical situation.

IMPROVING THE STRAIGHT ANALOG

Four general techniques have been proposed to eliminate the difficulty of working with large numbers of histories. By means of these techniques or combinations of them, it is possible in many problems to reduce to about 10^3 the number of histories required for a p.p.e. of 10%. These techniques are:

1. The use of random numbers to evaluate integrals representing the first, second, third, *etc.*, scattered beams. Various tricks that can be used to do this are discussed in the section on numerical integration. They could also be classified under the other techniques but are easier to discuss under this topic.

2. Replacement of the physical situation by a pseudomathematical analog with a solution of known relation to the original problem but with much larger values for P. It is then possible to use a reasonably small sample and still get an acceptable error.

3. A study in greatest detail of the neutrons most likely to penetrate the shield. This amounts to quota sampling,* stratified sampling, systematic sampling, or some combination of these. Various particle-splitting techniques usually come under this classification.

4. Development of some efficient statistical estimation procedure to utilize as much of the information in the life history as possible, rather than merely to count the number of particles that

* In this report "quota sampling" is used to describe somewhat more general techniques than would ordinarily be considered under this classification. As used here, it is sometimes called "importance sampling."

succeed in penetrating the shield and to throw away the rest of the calculated information.

In discussing these techniques, many suggestions will be made. When these suggestions are applied in actual computations, a proper balance should be maintained between doing a small number of complicated histories and a large number of simple histories.

Since, however, the error is proportional to $1/\sqrt{N}$ where N is the number of independent histories, it is usually more efficient to reduce the error by improving the technique, rather than to increase the number of histories. Even if a technique increases the accuracy by only a factor of 1.4, it may be worth using, because it cuts down the number of histories required for a given error by a factor of two. For this reason, it is necessary to discuss techniques which give only a minor improvement, as well as the important techniques.

Integration by Random Sampling

The first technique essentially poses the problem of estimating efficiently multiple dimensional integrals. Since this technique is discussed principally for the light it throws on the problems involved and not because it is actually used in practice, the discussion will be restricted to single and double integrals.

Consider first the evaluation of the single integral

$$J = \int_a^b g(x)f(x)dx \qquad (3)$$

where $g(x)$ is a given function of x and $f(x)$ is a probability density. This means merely that $f(x)$ is positive and that $\int_a^b f(x)dx = 1$. J is called the average or expected value of $g(x)$. It can be shown that if N independent values of x are picked from the distribution $f(x)$, J can be estimated by

$$J_1 = \frac{1}{N}\sum_{i=1}^{N} g(x_i) \qquad (4)$$

This is a better estimate than the one given in the first part of the report for the problem of Eq. 1. However, the error now depends on the form of $f(x)$ and $g(x)$. For large N, J_1 is normally distributed; an estimate of the probable error is

$$0.6745\sqrt{\frac{1}{N^2}\sum_{i=1}^{N} g^2(x_i) - \frac{\bar{J}_1^2}{N}} \qquad (5)$$

Equations* 4 and 5 generalize in obvious fashion to multiple integrals.

There is, however, a better method of estimating J. It can be written as

$$J = \int_a^b \frac{g(x)f(x)}{f^*(x)} f^*(x)dx \qquad (6)$$

$$= \int_a^b g^*(x)f^*(x)dx$$

where $f^*(x)$ is an arbitrary probability density function and $g^*(x) = g(x)f(x)/f^*(x_i)$. The estimate is now

$$J_2 = \frac{1}{N}\sum_{i=1}^{N} \frac{g(x_i)f(x_i)}{f^*(x_i)} \qquad (7a)$$

where the x_i are picked out of the distribution $f^*(x)$ rather than $f(x)$. The estimate of the probable error is

$$0.6745\sqrt{\frac{1}{N^2}\sum_{i=1}^{N} \frac{g^2(x_i)f^2(x_i)}{f^{*2}(x_i)} - \frac{\bar{J}_2^2}{N}} \qquad (7b)$$

It should be noted that Eq. 7 is the same as Eq. 4 except that $g(x_i)$ is weighted with the factor $f(x_i)/f^*(x_i)$.

If f^* is taken equal to gf/J, then the probable-error estimate comes out identically zero. In other words, there always exists a best $f^*(x)$ for which a sample of one gives the exact answer. However, in order to use this best estimate, the answer must be known in advance. In practice all that can usually be done is to approximate this best function by an $f^*(x)$ arrived at by the use of physical intuition, or by taking advantage of preliminary calculations. Considerations relevant to the

* "Equations" is used here as a generic term.

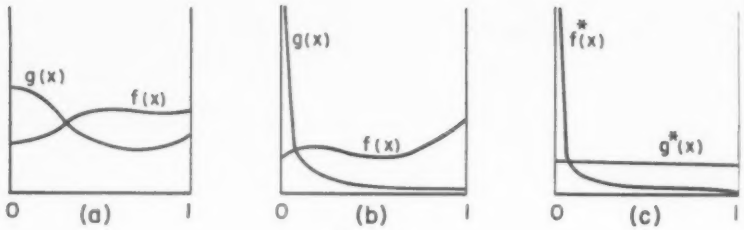

FIG. 3.

choice of an approximate $f^*(x)$ will be discussed in the second part of this article in the section on quota sampling.

However, some diagrams may make things clearer at this point. In Fig. 3(a) is shown a typical $f(x)$ and $g(x)$ with which no trouble would be expected. An estimate of the sort illustrated in Eq. 4 would be satisfactory. Fig. 3(b) is a case where an estimate as in Eq. 7 would be necessary. In this case $f(x)$ is such that most of the values of x sampled lie close to one, while the important values of x [because of the peak of $g(x)$] lie close to zero.

If the optimum transformation is made, then, as far as the sampling is concerned, Fig. 3(b) is turned into Fig. 3(c), the ideal sampling situation. However, if a less efficient transformation is made, and there is still a spike in the graph of $g^*(x)$ after the transformation, it may occur that $f^*(x)$ still is such that only comparatively rarely do we get a value of x in the region of the spike of $g^*(x)$. In that case (unless a large sample is taken) most of the time we will get an underestimate of the integral and only very occasionally an overestimate. Since underestimates of the value of the integral are usually associated with underestimates of the probable error and *vice versa*, the computer will be in danger of accepting the former but not the latter. There is a further discussion of this point at the end of Part II of this article.

Another technique that is often efficient is to combine numerical or analytical integration with random sampling. For example, one estimate of

$$I = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} g(x,y)f(x,y)dxdy$$

is

$$I_1 = \frac{1}{N}\sum_{i=1}^{N} g(x_i,y_i) \qquad (8)$$

where the x_i and y_i are picked at random from the distribution $f(x,y)$. Another estimate which uses a combination of random sampling and analytical integration and has a smaller error than Eq. 8 is

$$I_2 = \frac{1}{N}\sum_{i=1}^{N}\int_{-\infty}^{\infty} g(x_i,y)f_{x_i}(y)dy \qquad (9)$$

where $f_x(y)$, defined as the *conditional* distribution of y with respect to x, is equal to $f(x,y)/f(x)$. $f(x)$ is called the *marginal* distribution of x and is defined as $\int_{-\infty}^{\infty} f(x,y)dy$. The conditional distribution $f_x(y)$ is the probability density function for y when x has been fixed, and the marginal distribution $f(x)$ is the probability density function of x for any value of y. The x_i in the second estimate for I are picked out of the marginal distribution.

In general, this method is useful only when it is very easy to calculate $\int_{-\infty}^{\infty} g(x_i,y)f_{x_i}(y)dy$. That part of the integration which is hard to do (with respect to x) is still done randomly. This is an instance of the general rule that there is of course *no advantage in*

estimating by random sampling that which can be done easily by an exact method. Like many rules, this is not always true, but it is always worth while to consider combining exact and random techniques when the error is reduced more than the labor is increased.

These considerations are relevant to the neutron problem because a division into difficult and easy parts can be made. For example, roughly speaking, characteristics like absorption or the first and last collisions can be done exactly, and the rest of the life history sampled. These things will be discussed in somewhat more detail in the section on the fourth technique.

It is possible to achieve a sort of compromise between the estimates in Eqs. 8 and 9 by picking several values (say M_i) of y at random for every x_i. The estimate for I is then

$$I_3 = \frac{1}{N}\sum_{i=1}^{N}\frac{1}{M_i}\sum_{j=1}^{M_i} g(x_i,y_{ij}) \quad (10)$$

where y_{ij} is picked at random from the conditional distribution $f_{x_i}(y)$, and, as before, the x_i are picked from the marginal distribution of x. [Separating $f(x,y)$ into $f(x)f_{x_i}(y)$ and then picking first x and then y in the manner described above, is a standard method for choosing a two-dimensional point at random and can easily be generalized to n dimensions.]

Estimates of the type illustrated by Eq. 10 are useful if more of the error is due to variations in the y space rather than in the x space. In some problems it is more work to calculate the angle and energy history than the spatial history, but most of the error seems to be introduced by the latter. To compensate this, it might be advisable to calculate several spatial histories for a single angle or energy history, and to use the estimate corresponding to Eq. 10. In general, this last method is used to calculate certain types of histories in more detail than others. Any of the splitting processes is an example of this method.

The Exponential Transformation

Only one example of the second (mathematical analog) technique will be given. Assume a plane slab with a linear absorption coefficient $\mu(a)$. A pseudoproblem can be set up with a new linear absorption coefficient $\bar{\mu}(\alpha) = [\mu(\alpha) - c\cos\lambda]$, in which, as is shown below, the probability of transmission $\bar{P}$ is e^{ca} times P, the actual probability of transmission. Since the percent error goes roughly as $1/\sqrt{\bar{P}} = e^{-ca/2}/\sqrt{P}$, this transformation reduces the percent error by a factor of the order of $e^{ca/2}$.

The pseudoproblem is set up as follows. The function $\psi(x,\alpha,\lambda)$, which gives the average number of neutrons per unit volume, per unit energy, per unit solid angle at the point x, is first defined. It is well known that this function can be obtained by solving the following (transport) equation

$$\cos\lambda\frac{\partial\psi}{\partial x} + \mu\psi = \int\int k(\alpha',\lambda',\alpha,\lambda)\sigma(\alpha')\frac{v(\alpha')}{v(\alpha)}\psi(x,\alpha',\lambda')\sin\lambda' d\lambda' d\alpha' \quad (11)$$

and that the probability of transmission is

$$P = \int\int\psi(a,\alpha,\lambda)v(\alpha)\cos\lambda\sin\lambda d\alpha d\lambda \quad (12)$$

Here, $v(\alpha)$ is the velocity of the neutron; $k(\alpha',\lambda',\alpha,\lambda)$ is a function that, essentially, gives the probability that a neutron with energy α' and angle λ' scatters to energy α and angle λ; $\sigma(\alpha)$ is the reciprocal of the scattering mean free path; and $\sigma(\alpha)/\mu(\alpha)$ is the probability of survival of a neutron after it has had a collision.

The substitution

$$\bar{\psi}(x,\alpha,\lambda) = e^{cx}\psi(x,\alpha,\lambda)$$

is made where c is an arbitrary constant less than the minimum value of $\mu(\alpha)$. If substituted into the transport equa-

(Continued on page 37)

Fire Protection Precautions for URANIUM SCRAP AND POWDER

Fire properties of uranium scrap are discussed with emphasis on its pyrophoricity. Here are safe procedures for storage, handling, disposal, and shipment. ICC rules for common-carrier shipment are reviewed and the effect of various extinguishing agents on burning uranium scrap is evaluated.

By Edward J. Kehoe, Francis L. Brannigan, and Merril Eisenbud

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United States Atomic Energy Commission

URANIUM METAL is pyrophoric which means that in finely divided form it may ignite spontaneously on contact with air. Although possible with either dry or moist uranium powder, such a reaction occurs more readily with the powder in a moist state at slightly elevated temperatures. Dried uranium powder can be ignited also by rough handling. Uranium turnings and chips are easily ignited by an outside source of ignition.

The term "uranium scrap" is used in this paper to include uranium turnings, chips, borings, sawdust and powder. Such miscellaneous scrap may include material of all sizes from dust to turnings and contain oil, water, and such foreign matter as floor scrapings, organic waste, *etc.*

Storage . . .

The amount of uranium scrap in storage should be kept to a minimum. Protection is increased through isolation and separation of the material on hand into small batches. Fire-resistive storage facilities are recommended.

The temperature of a mass of burning uranium approaches 2300° F; accordingly, it is necessary to isolate uranium storage from other combustible materials.

Scrap may be stored under a mineral oil or under water. However, in the case of the water, provision must be made for the safe ventilation of the resultant hydrogen gas since the scrap slowly oxidizes in contact with water and releases free hydrogen. Consequently, storage under a mineral oil is generally preferable to storage under water.

The storage of scrap only partially submerged in oil or water is dangerous. Ignition is very apt to occur at the liquid line. The reaction is particularly severe in the case of water since the water boils off through the mass of burning metal with the liberation of large quantities of hydrogen. (Remember that hydrogen has an unusually wide explosive range, 4% to 75%. In one such fire involving an insufficiency of water, holes were burned through a metal drum by the fire and hydrogen flames several feet long shot out in addition to flames ten feet high from the top

of the drum.) If the liquid is oil, it too will probably ignite and add to the fire. By all means, avoid leaving oil- or water-moist scrap exposed to the air.

When scrap is not stored properly, as for example when it is only partially covered with oil or water, incipient spontaneous ignition can usually be detected by the fact that the container becomes heated; there is usually a marked increase in temperature which can be detected by the hand for some time prior to ignition.

Automatic sprinkler systems provide satisfactory protection for uranium turnings, chips, and borings and for the small quantities of sawdust or powder generally encountered in a machine shop or laboratory. While hydrogen is evolved from the water, it burns off readily under control and the sprinklers prevent the extension of the fire. In the unusual cases where extremely large quantities of uranium dust or powder may be involved, an inerting system, which utilizes a gas that is non-reactive with uranium (argon, for instance), may be in order.

(See the section on *Fire Control* for a discussion of fire extinguishers.)

Laboratory Handling . . .

In handling uranium scrap, every possible source of heat or spark should be eliminated. It is advisable to handle the material wet or under an argon atmosphere. Specially constructed explosion-safe argon dry boxes have been found very satisfactory where extremely pyrophoric forms are involved. Actually, extremely pyrophoric forms of uranium powder may burn so rapidly as to have the effect of an explosion. If, for some reason, ordinary laboratory glassware is used in lieu of such a dry box, safety glass screens and face shields are minimum protection. The work area should be kept clean of flammable liquids and other materials that might cause fires which would spread to the uranium. Quantities exposed should be kept to a minimum.

Disposal of Scrap . . .

Uranium scrap may be disposed of by controlled oxidation, by safe shipping to a recovery facility, or by conversion to a compact form to reduce the exposure to air. Specifically, these methods include the following:

Wet burning
Dry burning
Shipment under oil
Nitric acid oxidation
Degreasing, briquetting and vacuum casting
Shipment under argon

Each is briefly described below.

Wet burning. This method requires special equipment in which uranium scrap is oxidized under water by means of steam jets. Hydrogen is liberated. The process is carried out at the boiling point of water. An advantage of this method is that atmospheric contamination is reduced to a minimum. This method is desirable only at locations where fairly large quantities of material must be disposed of on a recurring basis.

Dry burning. The most expeditious and least expensive method for the disposal of uranium scraps by conversion to oxide is by direct dry burning in air.

For a quantity not exceeding five pounds, the scrap may be spread out on a steel plate in an open area and burned to oxide by the flame of an oxyacetylene torch. The worker should be protected by a welder's face shield and a metal

fume respirator. The scrap should be raked to insure that all the metal goes to oxide.

Where larger quantities are involved, a steel cased incinerator with heavy steel flooring is necessary. It should be equipped with a continuous source of combustion to maintain a satisfactory rate of combustion, a rake to permit turning over the material at frequent intervals, an exhaust system to a suitable flue, and dust collection apparatus that will withstand hot gases and possible incandescent particles. A muffle furnace has been used successfully with very low loss.

Shipment under oil. In the event that it is impossible to dispose of uranium scrap by oxidation, the scrap may be shipped under a mineral oil; however, this method should be avoided if at all possible.

Nitric acid oxidation. Small quantities of uranium scrap can be oxidized to uranyl nitrate with nitric acid. The reaction should be performed in a well ventilated hood and in a container sufficiently large to prevent boil-over. The vent is important because of the highly toxic nitric oxide fumes and hydrogen evolution.

Degreasing, briquetting and vacuum casting. This method requires extensive equipment and involves the complete degreasing of the material, removal of impurities and briquetting at pressures of 15,000 to 20,000 psi. It is practical only for the disposition of large quantities of material on a production basis. Actually, it is concerned with converting the scrap to a readily usable form rather than with simply converting it to oxide for disposal.

Shipment under argon. In unusual cases, it may be necessary to ship fine uranium powder as such without conversion to oxide. Under such circumstances, it is possible to ship small quantities of the powder under an atmosphere of argon and at dry ice temperature. Such shipments, if made, should be by courier rather than by common carrier.

Fire Control . . .

The best fire protection for uranium scrap is provided by keeping quantities small and separated, by segregating the scrap from other flammable materials and by handling and storing uranium in locations where a fire can burn out.

Fires in machining operations can be avoided by prompt removal of scrap out of the region where glowing turnings fall. Formation of a heavy oxide layer will extinguish the combustion of an isolated metal turning. If a small fire occurs, it can be extinguished by a gallon or so of the coolant; for this purpose an open top can of the coolant should be kept at hand.

G-1 powder (a commercial preparation with a graphite base), graphite chips, powdered talc or *dry* sand are useful in uranium scrap fires for controlling radiant heat, spatters and fumes. A supply of at least one of these agents should be available at all locations where uranium scrap is handled.

Ordinary fire extinguishers are not suitable. Uranium powder can burn in an atmosphere of carbon dioxide (which eliminates CO_2 extinguishers) and reacts to nitride in an atmosphere of nitrogen. The reaction with carbon dioxide also precludes dry-chemical extinguishers since they depend on the heat of the fire to liberate CO_2 from the breakdown of the bicarbonate of soda. Carbon tetrachloride extinguishers should not be used because of the undesirability of releasing carbon tetrachloride fumes in a confined space and because the hot

metal present may possibly cause decomposition of the carbon tetrachloride. Soda-acid and foam extinguishers are not recommended since they may cause scattering of the burning material and at best require extremely skillful handling to have any beneficial effect on burning uranium. Hose streams should be avoided. However, as mentioned in the section on *Storage*, automatic sprinklers are satisfactory if an extremely large quantity of powdered uranium is not involved; this would by no means constitute the usual situation.

Inhalation of the fumes from burning uranium metal should be avoided. If the burning occurs under controlled conditions, such as the burning of a small quantity in a laboratory, the hoods ordinarily used in handling the uranium will provide sufficient ventilation. However, if the burning does not take place under controlled conditions, approved breathing apparatus should be worn.

ICC Regulations . . .

The Interstate Commerce Commission regulations concerning radiation are found in Supplement 18 to Freight Tariff #4, Sections 366-369. (Shippers are referred to the appropriate freight tariff, Civil Aeronautics Authority or Postal Regulations for exact packaging and labeling information on radioactive materials.)

The limitation on the amount of uranium permitted to be shipped by express in one package is set at that amount disintegrating at the rate of 10^{11} atoms per second, which would be approximately 17,000 pounds. This limitation is obviously of little significance with respect to the weight of uranium metal in express shipments. The minimum amount requiring labeling is set at that amount disintegrating at the rate of 50×10^6 atoms per second, which would be approximately 8.5 pounds.

While the regulations of the Interstate Commerce Commission are not presently directed towards the pyrophoric properties of uranium scrap, the general regulations require the shipper of dangerous articles to describe, pack and mark his packages properly and inform the carrier's agent of the character of their contents. Shipments of scrap under oil should be made by courier rather than by mail or common carrier.

Random Sampling Techniques *(Continued from p. 33)*

tion, an equation for $\bar{\psi}$ is obtained

$$\cos\lambda\frac{\partial\bar{\psi}}{\partial x} + (\mu - c\cos\lambda)\bar{\psi} = \int\int\frac{k\sigma v\bar{\psi}}{v}\sin\lambda' d\lambda' d\lambda' \quad (13)$$

Equation 13 corresponds to a problem with a $\bar{\mu} = \mu - c\cos\lambda$ and a survival factor of $\sigma(\alpha)/[\mu(\alpha) - c\cos\lambda]$. If the survival factor turns out to be greater than one, it corresponds to a fission. It is not necessary, however, to let the neutron take a chance of dying [if $\sigma/(\mu - c\cos\lambda) < 1$] or splitting [if $\sigma/(\mu - c\cos\lambda) > 1$], but this quantity can be carried along as a weighting factor.

The probability for transmission P in the pseudoproblem is given by

$$\bar{P} = \int\int\bar{\psi}(a,\alpha,\lambda)v(\alpha)\cos\lambda\sin\lambda d\lambda d\alpha = e^{ca}\int\int\psi v\cos\lambda\sin\lambda d\lambda d\alpha = Pe^{ca} \quad (14)$$

* * *

In the second part of this article, quota sampling, parametric studies, splitting, statistical estimation, and the reliability of the various methods will be discussed.

PILE NEUTRON RESEARCH TECHNIQUES—II*

All but one of five reactors in operation in the U. S. are of the thermal type, making available experimentally valuable thermal neutrons. Techniques and apparatus for use both inside and outside the pile are detailed in this article.

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THE FIRST MEASUREMENTS made with chain-reacting piles utilized the high intensities of thermal neutrons available with the pile. Although the techniques discussed in the first part of this article (NU, Feb. '50, p. 5) have made measurements possible at higher energies, it is still true that the majority of the experiments with piles involve thermal neutrons. In the few years that chain-reacting piles have been available for research purposes, a great variety of techniques and instruments has been developed to utilize thermal neutrons.

A natural division of the methods used is again based on location, that is, whether the neutrons are used inside the lattice where one has the advantage of intensity, or outside the pile where the advantage is the collimation available with beams of thermal neutrons.

Thermal Neutrons Inside Pile

The average substance irradiated inside the pile will be activated mainly by thermal neutrons because of the high values of thermal neutron cross sections. Thus the whole field of activation of radioisotopes for experimental use falls in the present category. In addition, however, thermal neutrons inside the pile can be used directly for many measurements.

Neutron activation. Calculation shows that one mole of a substance, with an activation cross section of one barn, when placed inside a pile with a flux of 10^{12} and irradiated to saturation, will have an activity of 18 curies after removal from the pile (see equation in next section). This fact illustrates the great importance of the available experimental piles for production of radioactive materials for experimental use.

Radioisotopes, of course, exhibit a tremendous range in half-lives, from values exceeding millions of years down to less than microseconds, and the methods of production and use vary accordingly. Those isotopes of long half-life are simply bought from the Isotopes Division of the Atomic Energy Commission at Oak Ridge (*34*, *37*, *38*).‡ The isotopes of intermediate half-life have been made extensively in the piles at Oak Ridge and Argonne for shipment to nearby research centers. Half-lives as short as several hours have been handled in this way.

Shorter-lived activities must be studied at the laboratory where the pile is

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† Part of this paper was written while the author was at Argonne National Laboratory, Chicago, Illinois.

‡ Note that references *1–33* appeared in part one of this article, and that reference numbers in this part begin with *34*.

located; those of extremely short lives must be studied directly at the pile itself. The research piles are all equipped with pneumatic transfer devices which can remove samples from the pile in times of the order of seconds. In measurements of the delayed neutron activities, Hughes, Dabbs, Cahn and Hall (*35*) used a rapid transfer device called a "rabbit" which could move a uranium sample from a position at the edge of the pile lattice to a well-shielded neutron counter in 0.4 sec. The apparatus is shown in Fig. 7,* and the rapidly changing counting rate, as well as timing signals, were recorded on electrocardiograph tape, a section of which is shown in Fig. 8. Recently (*36*) an extremely high-speed rabbit, which enables removal of a small sample from the pile in 0.1 sec, has been installed at the Oak Ridge pile.

* Figures 1–6 appeared in part one of this article; Fig. 7 is the first illustration in this part.

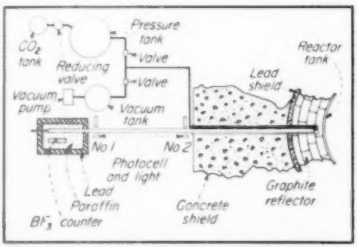

FIG. 7. Schematic diagram of the pneumatic transfer device, or "rabbit," for short irradiations. Sample is blown from a position near the pile lattice to a counter in 0.4 sec. Photocells are used to determine time at which sample left the pile

Activation cross sections. Activation cross sections for thermal neutrons can be measured inside the pile in much the same way as that described in the first part of this article for resonance neutrons. The effect of resonance neutrons can be eliminated simply by activation with and without a cadmium shield surrounding the sample and determination of the difference, the "cadmium difference," which is proportional to the activation of thermal neutrons alone. If the flux in the pile is known and if the activated material is counted on a calibrated (*39*) Geiger-Müller counter (so that the disintegration rate can be obtained from counting rate), the activation cross section can be calculated simply:

$$C = Nnv\sigma_{act}$$

In this expression C is the disintegration rate of the sample, containing N nuclei, when irradiated to saturation. Both the flux and the counter calibration can be obtained by absolute

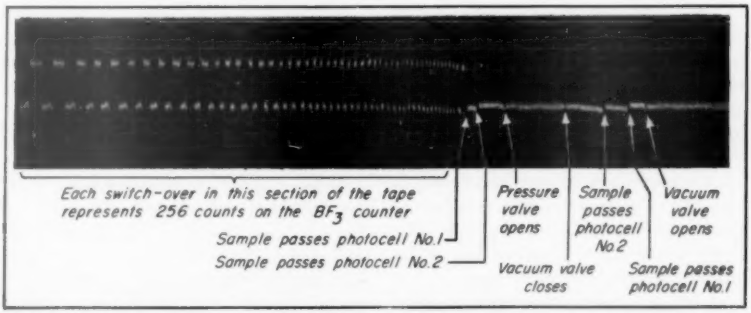
Each switch-over in this section of the tape represents 256 counts on the BF_3 counter
Sample passes photocell No.1
Sample passes photocell No.2
Pressure valve opens
Sample passes photocell No.2
Vacuum valve opens
Vacuum valve closes
Sample passes photocell No.1

FIG. 8. Electrocardiograph tape showing the timing signals and initial portion of the decay curve of a short-lived activity produced in the rabbit (Fig. 7). Vertical lines each represent 0.04 sec. The signal when the pressure valve closes is lost among the counter signals

measurements (see "neutron standardization" next month), but in practice it turns out to be much simpler to measure the activation cross sections relative to some standard material. The use of relative measurements makes it unnecessary, in general, to take into account the wide energy spread present in the thermal neutron flux. (Both standard and sample will usually possess the same variation of cross section with velocity.)

The standard material, such as gold, is one that has an absorption cross section much greater than its scattering cross section, so that the former can be inferred accurately from a transmission measurement. The transmission measurement, made with a neutron beam, gives the total cross section quite accurately. Absorption is obtained by subtraction of the scattering cross section. The standard, as well as the unknown, must have a known decay scheme so that no uncertainty will exist in the conversion from counting rate to disintegration rate.

A detailed series of activation measurements was carried out by Seren, Friedlander and Turkel (*40*) at Argonne. This series began shortly after the first graphite pile was put in operation. At first, cross sections were calculated from absolute flux and counter calibration in the manner just described. Later, they were converted to relative measurements in terms of standards of rhodium and gold, whose total cross sections had been measured by Fermi by means of transmission. When the higher flux of the Argonne heavy-water pile became available, it was possible to activate materials in the thermal column and thus determine thermal activation cross sections without taking cadmium differences.

If the activation cross section for a particular isotope is known, the activity resulting from irradiation in the pile can be used to determine the amount of that isotope present in a sample. The characteristic half-life of the isotope is used to separate its activation from that of other constituents of the sample. This method of "activation analysis" has been treated at length in an article by Boyd (*41*), who describes its use in the analysis of metals and alloys. In certain favorable cases one part per billion of impurity may be detected. Brown and Goldberg (*42*) have used activation analysis to determine the gallium and rhenium content of meteorites, and Tobias and Dunn (*43*) have analyzed biological tissue by the same method.

Absorption cross sections. A method of measuring the thermal absorption cross section (*i.e.*, cross section for all absorption processes whether activation results or not) by the effect on pile reactivity was developed quite early (*44*) because of the importance of this method for the determination of the purity of such materials as graphite. The absorption is measured by placing a sample inside the pile and determining the resultant effect on the pile reactivity, which is measured in units of "inhours." One inhour is that amount of reactivity which will cause a pile's power level to rise exponentially with a period of one hour. One inhour of reactivity corresponds to a reproduction constant, the k described in the first part of this article, only $\frac{1}{400}\%$ greater than unity.*

In principle, the measurement is made by setting k for the pile at exactly unity (*i.e.*, pile power constant) with the control rod, placing the absorbing material inside the pile, then removing enough control rod to obtain a unit k again. The change in reactivity of the pile can then be read from the calibrated control rod.

* The relationship of the pile period to the reactivity, which is determined by the properties of the delayed neutrons, is discussed in reference *35*.

Actually, however, the change in reactivity is determined from the rate at which the pile drifts upward or downward in intensity when k is very near unity. The conversion from inhour effect to square centimeters of absorption could in principle be calculated from the constants of the pile, but, as usual, the comparison constant is determined from a standard material, in this case boron, whose absorption cross section is already known from transmission measurements. If the unknown is a $1/v$ absorber, as is boron, the resulting cross section (usually given for 2,200 m/sec) is independent of neutron velocity distribution in the pile. If not $1/v$, a correction, usually small, must be made for resonance absorption (see part one of this article).

The method just described came to be known as the "danger coefficient" method of measuring absorption cross sections because of the obvious danger of neutron-absorbing impurities in pile materials. More recently, the danger coefficient method has been replaced to a large extent by the "oscillator" method of measuring absorption cross sections. The oscillator method, which is used both at Argonne (*45*) and Oak Ridge (*46*), consists of pushing a sample into the pile at regular intervals and observing the cyclic variation in pile intensity (See Fig. 3 of part one of this article). The amplitude of the intensity variation is proportional to the neutron absorption of the sample. Absolute values are obtained by comparison with boron.

The oscillator method is somewhat more sensitive than the reactivity method—about 10^{-3} square centimeters of absorption cross section (corresponding to a cross section of about 0.0016 barns for a one mole sample) can be detected. The oscillator method, however, has entailed more difficulty in disentangling effects caused by true neutron absorption from several extraneous effects having to do with neutron scattering. The interfering scattering effects become important only when materials with scattering cross section many times greater than absorption are measured.

At the present time the absorption cross sections of those elements which can be obtained in very pure form are known (*47*) to within 5% in most cases. The main difficulty with the others (except where scattering is much larger than absorption) is the presence of impurities, rather than uncertainties in the cross-section measurement technique. Except for elements which have no isotopes, it is difficult to compare absorption cross sections, measured for the normal element, with activation cross sections, which refer to specific isotopes of the element. Recently, however, the amounts of separated isotopes available have become large enough (of the order of 0.1 gm) to make isotopic absorption measurements possible. A few separated isotopes have been measured with the Oak Ridge oscillator (*48*). The results obtained so far check the activation cross sections reasonably well. A comparison of isotopic activation and absorption will help to uncover nuclear states caused by absorption and unknown by activation, such as isomers whose half-lives are long enough to have escaped detection.

Thermal Neutrons Outside Pile Lattice

Neutrons which emerge from the pile lattice through the thermal column attain a Maxwell velocity distribution in the column and are available for use either inside the thermal column itself, or as neutron beams emerging from the column. Irradiation inside the thermal column possesses no outstanding advantage over thermal irradiation in the pile because pile irradiation is of much higher intensity and the effect of thermal neutrons can be iso-

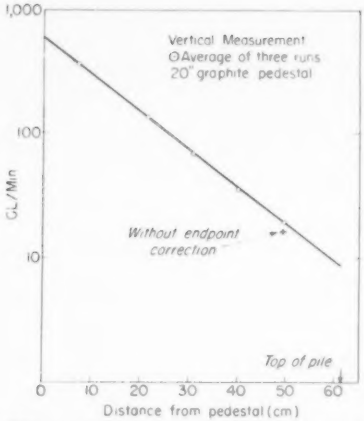

FIG. 9. Neutron distribution in the vertical direction in a block of material in which neutrons are diffusing upward

lated by measuring the cadmium difference.

Neutrons from the thermal column are used mainly as they emerge from the column. In this way they have been used for hundreds of experiments which cover a host of applications. The neutrons can be allowed to diffuse in an uncollimated manner from the face of the thermal column into a medium for diffusion studies, or can be formed into a roughly collimated beam by means of a hole opened part way into the column (see Fig. 1 of part one). By either method a flux of extremely well thermalized neutrons of magnitude about 10^7 is available. It is this fact which has made the thermal column of such extreme value for neutron research.

Additional collimation, in the form of narrow slits in cadmium sheets, can produce beams of such small divergence that diffraction and mirror reflection of neutrons can be accurately measured. The principal techniques which have been developed for the use of the thermal column are described in the following pages, although no effort has been made to cover all the specific experiments which have been performed at thermal columns. The questions of the exact velocity distribution and number of neutrons present in the column will be discussed later in the section on standardization.

Diffusion measurements. Neutrons move through the thermal column by diffusion. If a block of low-absorption material is placed against the surface of the column, the neutrons will diffuse through it in the same manner. The neutron intensity will decrease exponentially with distance in the block if it is sufficiently long (several relaxation lengths). The "diffusion length," L, for the material of the block (assumed to be of square cross section with side a) will be given by

$$\frac{1}{L^2} = \frac{1}{l^2} - \frac{2\pi^2}{a^2}$$

where l, the "relaxation length," is the measured distance along the length of the block for the neutron intensity to decrease by the factor e. In the direction perpendicular to the length of the block, the neutron intensity will follow a cosine distribution (for a block of square cross section), which extrapolates to zero slightly beyond the side face of the block (by an amount called the "augmentation distance") because of the finite neutron leakage from the faces of the block. The quantity a in the formula is actually the geometrical size of the block increased by twice the augmentation distance.

The neutron distributions are measured by small foils, such as indium, which are placed inside the block, activated, and then counted with a Geiger counter. Distributions measured in this way in a diffusing material are shown in Fig. 9 for the vertical direction (lengthwise) and in Fig. 10 for the horizontal. The point nearest the top of the block in Fig. 9 falls below the exponential curve because of neutron leakage, (this effect being com-

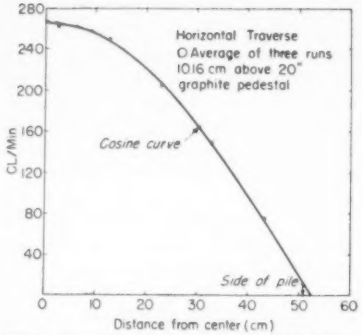

FIG. 10. Horizontal neutron distribution for the block of Fig. 9. Block is of square cross section, so the flux follows a cosine curve extending slightly beyond the edge of block

pensated by an "end correction"). The augmentation distance is clearly seen in Fig. 10.

The diffusion length L is related (*49*) to the average scattering and absorption cross sections of the material in the following way:

$$L^2 = \frac{1}{3N^2\sigma_a\sigma_s(1 - \overline{\cos\theta})}$$

where N is the number of nuclei per cubic centimeter, σ_a and σ_s are the absorption and scattering cross sections, and $\overline{\cos\theta}$ is the average cosine of the angle, θ, by which the neutron is deviated when scattered. The average cosine is about zero for heavy nuclei ($\overline{\cos\theta} = 2/(3A)$, where A is atomic weight). This formula is valid only when σ_a is much smaller than σ_s, a condition always satisfied in diffusion measurements.

A measurement of the diffusion length in a material is usually a determination of the absorption cross section, because the scattering cross section can be determined from a total cross-section measurement when the absorption is very small. For such materials of small absorption it would be difficult to measure the absorption by other methods, such as the pile oscillator, because of the interfering effect of scattering.

Measurements of the diffusion length in graphite were quite important as tests for the presence of small amounts of absorbing impurities in connection with the construction of the graphite piles. The method is still quite valuable for similar low-absorption materials.

Irradiation with thermal beams. When it is desired to study some effect which follows neutron absorption in an extremely short time, the method of irradiation in a beam of thermal neutrons is often the only method available. Examples of such phenomena are extremely short-lived radioactivities or the more short-lived "instantaneous" emissions such as protons, neutrons, fission fragments, and capture gamma-rays. Radioactivities with periods less than 0.1 sec cannot be studied with the rapid-transfer "rabbit" and must be measured without large movements of the sample.

One method which has been used only slightly is that of the rotating wheel containing the sample on its periphery. The rotation of the wheel carries the irradiated material through the beam of neutrons and past a counter where the decay of the sample is measured. The wheel method has been used by Muehlhause (*50*) at Argonne, but difficulty was experienced with the large background activity near the open beam.

In the study of very short-lived delayed-neutron periods, Hughes, Dabbs, Cahn and Hall (*35*) used a heavy shutter (Fig. 11) operated by gravity to obtain a 0.19-sec neutron burst for irradiation of a uranium sample. They then followed the decay of the delayed neutrons from the uranium by recording scaler pulses on an electrocardiograph tape. A very rapidly decaying delayed-neutron period of half-life 0.05 sec was discovered and measured in

this way (Fig. 12). Counters in this case were BF_3-filled proportional counters. No difficulty was experienced with the gamma and beta background at the thermal column.

No special techniques are needed for the study of the instantaneously emitted radiation. The major difficulty lies in separating the desired effect from the general background near the open hole in the thermal column. If the neutrons are allowed to diffuse through a block of bismuth before emerging from the thermal column, the intensity of gamma rays can be greatly reduced with only a small decrease in neutron flux. The neutron beam can be reflected from a crystal or a mirror and thus separated from the gamma beam, but a considerable loss in intensity results. The characteristics of the fission process can be studied using fission chambers (*51–54*), cloud chambers, or photographic emulsions (*55–57*). The neutrons from fission can be detected in various neutron counters and their number and energy distribution thus measured (*58, 59*).

Slow-neutron reactions in which heavy particles are produced [exothermic (n,p), and (n,α)] can be studied quite well in the cloud chamber. By

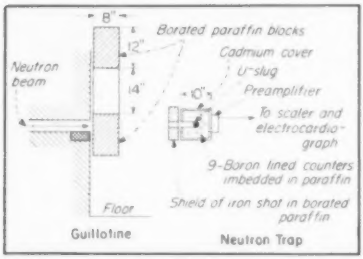

FIG. 11. Apparatus for production of very short (0.19 sec) neutron irradiations and measurement of short period delayed neutrons

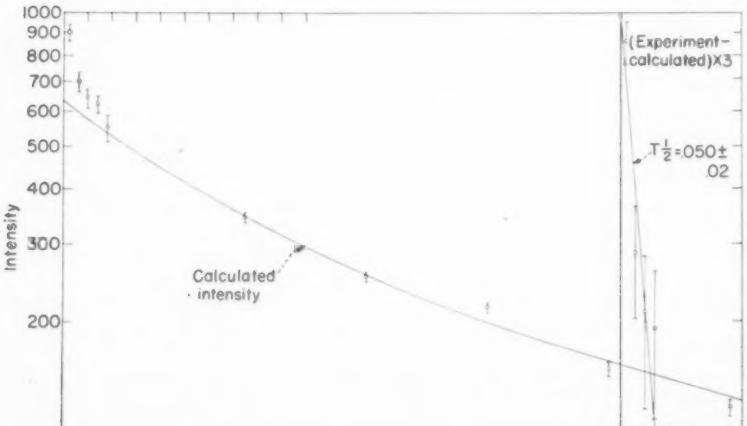

FIG. 12. A delayed neutron decay curve obtained with the apparatus of Fig. 11. Calculated intensity is based on five known delayed neutron periods longer than 0.4 sec. Difference curve, on the right, is interpreted as a new period of approximately 50 millisecond half-life

using He or H gas at low pressure, with a high electric sweep field, a low expansion ratio and a rapid expansion, the background fog caused by the intense beta background can be made quite negligible. Figure 13 shows the (n,p) reaction (*60*) in He^3. Background fog is indeed slight, although the beta and gamma intensity at the chamber was above tolerance (0.1 mr/8 h) at the time. A slight increase in the expansion ratio to the "normal" operating value would have resulted in complete fogging of the chamber.

An important problem of the instantaneous emission type is the measurement of capture gamma rays, which is made difficult by the general background. This problem has been attacked by measurement of Compton recoil electrons in the magnetic-lens spectrometer (*61*), by absorption (*62*), by pair spectrometer, by observation of pairs in a cloud chamber (*63*), and by photodisintegration in deuterium-impregnated emulsions (*64*). These methods all involve major difficulties, but gradual progress has been evident in the last few years.

Another example is the radioactive decay of the free neutron. This can be detected by identifying the beta particles (800 kev maximum energy) or the recoil protons (several hundred volts energy) which are produced by the decay of neutrons in a beam. Recent results obtained by Robson (*65*) and by Snell *et al* (*66*) seem to have demonstrated this decay, the neutron possessing a half-life of about 15 min.

Transmission and scattering measurements for Maxwell distribution of neutron velocities. When thermal beams were first available, many measurements were made of the simple transmission type, which give the total cross section averaged over the Maxwell distribution. The method of obtaining the total cross section from the transmission of a beam has already been described (section on "Resonance detectors" in part one of this article) as well as the fact that the thermal beam, as detected by a $1/v$ detector, has a Maxwell velocity distribution (see NU, Feb. '50, p. 5). For materials with absorption large enough that scattering is merely a correction, and for $1/v$ absorption, these transmission measurements can be interpreted to give the absorption cross section for a particular velocity.

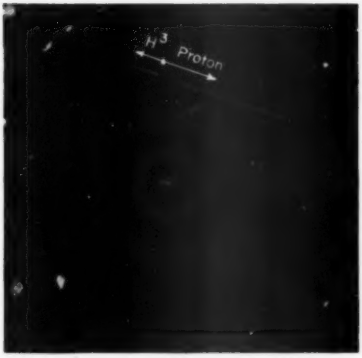

FIG. 13. The reaction He^3 (n, p) H^3 photographed in a cloud chamber operated so as not to show the intense beta background in the thermal neutron beam. Chamber is filled with normal He (containing 10^{-4} % He^3) at a pressure of 20 cm. The reaction can be identified by the presence of a short heavy track (the H^3 recoil nucleus) and a colinear light track (the proton)

As the neutrons move through such an absorber they are preferentially absorbed, and the average absorption becomes smaller, that is, the beam "hardens." The effect of this hardening for the case of a $1/v$ absorber and a $1/v$ detector, such as a thin BF_3 counter, has been calculated by Bethe (*67*). For a sample of such thickness that the transmission is about one-half, the cross section inferred from the transmission is extremely close to the cross section for the most probable

velocity in the Maxwell distribution, that is, 2,200 m/sec at room temperature. For other transmission values, the so-called Bethe hardening correction is taken from the curve calculated by Bethe and applied to the observed transmission to get the 2,200 m/sec value. (As 2,200 m/sec is the velocity of a neutron of energy kT with T = 293°, the cross section at this velocity is often referred to as the "kT cross section.")

If the absorption cross section is known from danger coefficient measurements, it can be subtracted from the measured total cross section to give the scattering cross section. Such scattering cross sections, however, are only averages over the thermal region, in which rapid oscillations actually occur because of crystal effects, and hence, while of great practical importance, have no simple relation to cross sections at particular energies.

The scattering cross section can also be measured directly by detecting the neutrons scattered from a sample. The intensity for such measurements is so low that background interference becomes troublesome, but the measurements can be carried out without undue difficulty. Again, the scattering cross section is only an average over the crystal-effect region and is useful only for applications where an average value is sufficient.

In general, although transmission and scattering measurements made with the complete Maxwell distribution have been of great practical value, to a large extent they have been replaced by the more precise techniques which have been developed for the use of monoenergetic neutrons. These techniques are described in the next sections.

Crystal diffraction. The use of single crystals for the production of monoenergetic beams of neutrons, that is as monochrometers, has already been discussed. The monochromatic neutrons

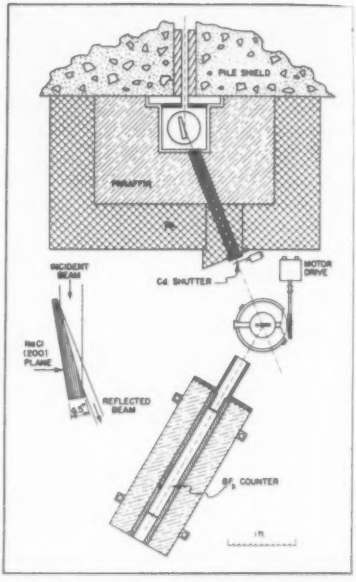

FIG. 14. Crystal diffraction apparatus used by Wollan and Shull at Oak Ridge

produced in this way in the thermal region, where the intensity is the highest, have been used extensively for the study of crystal structure by methods completely analogous to those used in X-ray crystal diffraction. A typical arrangement for neutron diffraction studies is shown in Fig. 14. A collimated beam of neutrons emerges from the hole through the pile shield and is incident on the first crystal, the monochrometer crystal. This crystal is set to reflect an almost "monochromatic" neutron beam of a wave length near the maximum intensity of the neutron distribution. A finite wave-length spread is present in the reflected beam because the crystal planes are not in perfect alignment (mosaic structure) and the neutrons in the incident beam do not move strictly parallel.

The crystal under study (either a single crystal or a powder) is placed

on the crystal table; diffracted neutrons are detected in the neutron counter mounted on the spectrometer arm. If a powder crystal is used, the Debye-Scherrer rings typical of a powder pattern are found as the spectrometer is rotated. If a single crystal is used, the crystal table and the spectrometer arm are geared together so that the latter rotates with twice the angular displacement of the former; the Bragg maxima are thus located. Single crystals have been used by Fermi and Marshall (*68*) in their investigation of the scattering amplitudes of various nuclei (the scattering amplitude, a, is related to the coherent scattering cross section, σ_c, by the relation $\sigma_c = 4\pi a^2$). The powder method has been used principally by Wollan and Shull (*69*) at Oak Ridge, both for measurement of scattering amplitudes and for determination of crystal structures.

The intensity of neutrons available for diffraction studies is so low that the work is considerably more time-consuming than the corresponding X-ray measurements. It is possible, however, that by use of multiple crystals and improved collimators, the intensity might be greatly improved.

The most promising feature of neutron diffraction is the possibility that hydrogen atoms can be located in crystalline substances. The location of hydrogen atoms is exceedingly difficult with X-ray because of the low scattering power of hydrogen, but for neutrons the scattering cross section of hydrogen in the average nucleus is much higher. The advantage of the large cross section of hydrogen is offset by the fact that most of the cross section is incoherent (because of the large spin-dependent scattering). Incoherently scattered neutrons will produce only a diffuse background in the diffraction pattern. Shull *et al* (*70*) have studied the structure of sodium hydride by using sodium deuteride because the scattering of the deuteron is largely coherent.

It hardly can be said that neutron diffraction is an established tool for study of crystal structure at the present time. The technique is in the investigative stage in which details of the mechanism of neutron scattering in crystals are still being elucidated.* In many ways the techniques of X-ray diffraction can be taken over directly to the neutron case, but there are additional factors, unique to neutron diffraction, which must be considered. Thus the various isotopes of an element in general have different scattering amplitudes (they may actually differ in sign); as a result incoherent or diffuse scattering will be produced because the isotopes are distributed at random in the crystal. In addition, for each isotope with spin different from zero, there are two scattering amplitudes corresponding to the cases in which the neutron spin adds to or subtracts from the nuclear spin in the scattering process. If these two amplitudes differ greatly, that is, if there is large spin-dependent scattering, then additional diffuse scattering will result, as in the case of hydrogen.

The results of several measurements have been published in which crystal diffraction has been used in investigations of a rather special nature. For instance, the effect of crystal orientation in polycrystalline aluminum resulting from metallurgical treatment has been shown by Arnold and Weber (*71*) by measurements of the transmission of the aluminum samples for monoenergetic neutrons. It is possible to show crystal effects by transmission because neutron absorption is extremely low in certain substances, whereas analogous measurements cannot be made by this method with X-rays

* See E. O. Wollan, C. G. Shull, "Neutron Diffraction and Associated Studies," NUCLEONICS **3**, No. 1, 8 and No. 2, 17 (1948).

because of the high absorption always present. Shull and Smart (*72*) have been able to detect the anti-ferromagnetic structure (domains in which the atomic magnetic fields add to zero) present in MnO because the magnetic scattering of neutrons leads to extra lines in the diffraction pattern. No such scattering would occur with X-rays, of course. Laue photographs have been obtained (*73*) by using special methods to intensify the effect of neutrons on a photographic plate, but even with rough collimation extremely long exposure periods were necessary. Using a modification of the standard crystal arrangement to give increased intensity, Chamberlain (*74*) has studied the diffraction of neutrons by liquids.

Mechanical velocity selectors and "choppers." The crystal monochrometer is usually used near the maximum of the thermal neutron distribution in order to obtain the highest possible intensity for neutron diffraction. Difficulties arise when the crystal is used to select neutrons of much lower velocity because of interference by higher order reflections of faster neutrons. From the Bragg formula $n\lambda = 2d \sin \theta$, it can be seen that neutrons of shorter wavelengths and higher values of n will be reflected at the same angle as those for which reflection is desired. When the crystal is set to reflect neutrons of quite long wavelength, the higher order reflections can be of much greater intensity than the first order because of the shape of the Maxwell neutron distribution. Because of this difficulty with higher order reflections, some type of mechanical velocity selector is more useful than the crystal for selection of extremely low neutron velocities.

A mechanical "chopper" designed by Brill and Lichtenberger (*75*) at the Argonne laboratory selects neutrons according to velocity by producing

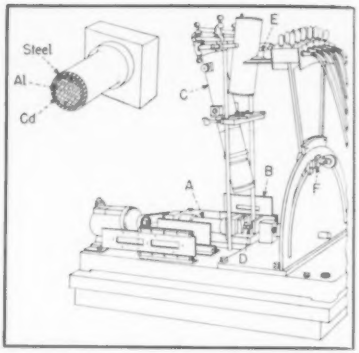

FIG. 15. Argonne slow-neutron chopper used for cross-section measurements in the energy range 0.001 to 0.3 ev. Rotating shutter, *A*, consisting of alternate layers of Al and Cd, is shown enlarged in the inset

bursts of neutrons whose time of flight to a detector is measured in much the same way as in the modulated-cyclotron method. The Argonne chopper, shown in Fig. 15, is a rotating cylinder (*A*) made up of alternate cadmium (6 mil) and aluminum (30 mil) sheets, driven by an electric motor at speeds up to 180 rps. As the cylinder rotates it transmits neutrons for approximately 3 deg twice each complete rotation. Thus, at 180 rps, bursts of neutrons of 45 microseconds duration are produced 360 times per second. The detector, a BF_3 proportional counter, is located 1.5 meters beyond the chopper, and the counts from the detector are switched to six scaling units at definite intervals after each neutron burst. The timing of the switching circuits is controlled by a beam of light from the source (*C*), reflected from a mirror (*D*) on the rotating shaft to a series of photocells whose positions can be adjusted at (*F*). Each scaler therefore records neutrons of a single velocity interval determined by the time of flight of the neutrons from the chopper to the detector.

The chopper has been used mainly

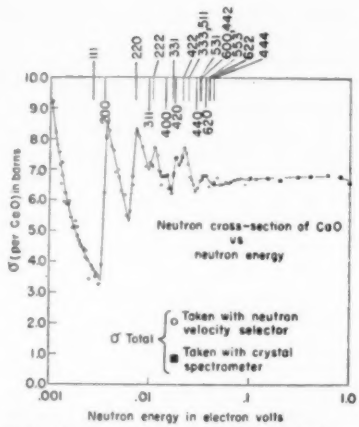

FIG. 16. Total cross section of CaO as measured with chopper of Fig. 15 (together with a few points obtained with crystal spectrometer). Marked variation in cross section in the region 0.003 to 0.03 ev is associated with reflection from various crystal planes (whose Miller indices are shown by the vertical lines)

for transmission, that is, total cross-section, measurements as a function of velocity for sub-thermal neutron velocities. Although the chopper will work up to 0.3 ev, above which energy Cd transmits neutrons, the crystal monochrometer is more useful in the range 0.03–0.3 ev. Below 0.03 ev, however, the chopper gives enough intensity so that total cross sections may be measured with a velocity resolution of 3%. The low energy limit is fixed by the intensity, and the best that has been done so far is about 0.001 ev, that is, a wavelength of 10 A.U. or a velocity of 400 m/sec.

In addition to its use for low-energy cross-section measurements, the chopper is extremely useful for the study of crystal effects by transmission through a polycrystalline sample. The relatively poor collimation of the chopper is of no disadvantage in a transmission experiment, since crystal effects are very noticeable in the energy range 0.001 to 0.03 ev. As the neutron wave length becomes greater than the spacing of a particular set of lattice planes, the transmission increases abruptly, and a curve of transmission *vs.* velocity can be interpreted in terms of the crystal structure of the sample as well as the orientation and size of its crystal grains. By this method, Fermi, Sturm, and Sachs (*76*) have studied the transmission of Be and BeO; Winsberg, Meneghetti, and Sidhu (*77*), the scattering amplitudes of several nuclei; and Krueger *et al* (*78*), the small-angle scattering of low-energy neutrons at grain boundaries.

The chopper is not a true velocity selector, for it passes neutrons of all velocities, which are then velocity-selected by time of flight. At the present time several true velocity selectors, designed for the low-velocity region, are under construction at Oak Ridge, Argonne, and Brookhaven National Laboratories. These selectors are all of the type in which a rotating shutter contains curved paths along which neutrons of only a narrow velocity range can proceed. Such shutters become true velocity selectors because they pass only a single neutron velocity which depends on the velocity of rotation and the neutron path in the shutter. These selectors will be especially useful for studies of neutron activation as a function of velocity inasmuch as activation measurements are impossible with the chopper. In theory, activation with monoenergetic neutrons is also possible with the crystal, but to date it has not been done because of low intensity relative to background and the necessity of working close to the direct beam.

Neutron polarization. High-intensity thermal neutron beams have proved to be extremely useful for studies of the production of polarized neutrons and their use as an experimental tool. The possibility of polariz-

ing the neutrons in a beam was first suggested by Bloch (*79*), who showed that the scattering cross section for neutrons by magnetized iron should be different for the two possible orientations of the neutron spin relative to the magnetic field. The difference in cross sections implies that a neutron beam, after passing through magnetized iron, should have a preponderance of neutrons with spins oriented in one direction. In this way a high degree of polarization could be produced in a very thick block of magnetized iron. The difference in cross section was shown by Bloch to arise from the term in the intensity caused by the interference of the neutron wave scattered by the magnetic field of the iron atom with the wave scattered by the nucleus. It was suggested that neutron polarization experiments would give valuable information on the interaction of neutrons with electrons and on the nature of ferromagnetism. The detailed theory of the passage of neutrons through magnetic materials was given by Halpern *et al* (*80*).

The first use of polarized pile neutrons was the measurement of the magnetic moment of the neutron by Arnold and Roberts (*81*), using the method of Alvarez and Bloch (*82*). Hughes, Wallace and Holtzman (*83*) carried out an extensive study of the process of neutron polarization and performed a few experiments in which the polarized neutrons were used to investigate ferromagnetic properties, such as the size of ferromagnetic domains and the law of approach to magnetic saturation.

At the present time the production of polarized neutrons by transmission through magnetized iron is well understood and in good agreement with theoretical expectations (*84*). Neutron beams of 60% polarization can be obtained by this method without undue loss of intensity; they are quite useful for such measurements as the depolarization of neutron beams in thin sheets of magnetic materials. The polarization of the beam emerging from the thin sheet is measured by observing its transmission through a second block of magnetized iron which acts as an analyzer, in a manner analogous to optical polarization experiments. Measurements of depolarization made in this way give domain size and domain orientation in a very direct manner (*85*), and the domain properties have been shown to be directly related to the metallurgical treatment of the iron sheets. Completely polarized neutron beams recently have been obtained by reflection from magnetized mirrors, by utilizing techniques of the next section.

Only limited applications have been made of highly polarized pile neutron beams to date. These applications have been mainly in the field of ferromagnetism, where polarized neutrons, acting as minute test dipoles, are particularly useful. The other field of utility for polarized neutrons is that of spin-dependent forces, but here the applications are made difficult because of the fact that the nuclei are oriented at random. Spin-dependent forces could be studied with non-oriented nuclear spins only by studying the depolarization of the scattered neutrons. This is made difficult by loss in intensity. Efforts are now being made to align nuclei by means of low temperature and high magnetic fields. If appreciable alignment can be produced, highly polarized neutron beams will be extremely useful for measurements with the aligned nuclei.

Neutron mirrors. The neutron flux from the thermal column is high enough so that a highly collimated beam of neutrons may be formed without a prohibitive loss in intensity. Fermi and Zinn (*86*) demonstrated the total reflection of neutrons from mirror surfaces at glancing angles in 1944. As such reflection takes place only for

angles of the order of a few minutes, the incident beam must be well collimated.

The equations governing mirror reflection of neutrons are closely analogous to those of optical or X-ray reflection. The index of refraction, n, for neutron waves in a medium is determined (*87*) by the amplitude, a_c, of the coherently scattered waves:

$$n^2 = 1 - \frac{\lambda^2 N a_c}{\pi}$$

Here N is the number of nuclei per cm³. The sign convention is such that a positive scattering amplitude is that of an impenetrable sphere. (Most nuclei have positive amplitudes.) It is important to note that the index depends only on the coherent scattering, independent of such incoherently scattered waves as those caused by lattice vibrations. It is just because the index depends only on the coherent amplitude that mirror reflection is a powerful method of measuring such amplitudes. The coherent scattering amplitude can also be measured by the intensity of the Bragg maxima with the crystal diffraction method, but in that case the results are affected by lattice vibrations.

The most direct method of measuring the index of refraction for neutrons is by means of the critical glancing angle, θ_c, for total reflection:

$$\theta_c = \lambda \sqrt{\frac{N a_c}{\pi}}$$

A measurement of the angle at which the reflection "disappears" (actually drops rapidly to a low value) for a given wavelength, λ, gives the coherent amplitude directly with no corrections. If total reflection occurs, it is known immediately that the sign of a_c is positive, for a negative amplitude would give only an extremely weak reflection. Fermi and Marshall (*68*) have measured the magnitude of several positive amplitudes by this method, and have shown that one or two others are negative.

When neutrons pass through unmagnetized iron, the scattering amplitude will have two values depending on whether the magnetic force on the neutron adds to, or subtracts from, the nuclear force (*88*). Thus iron is expected to be "doubly refracting." Such behavior was found (*89*) as an extremely small angle (about one minute) scattering of a finely collimated neutron beam in an iron block. The double refraction can be shown more clearly by reflection from an iron mirror because two distinct critical angles (*90*) are expected:

$$\theta_c = \sqrt{\lambda^2 \frac{N a_c}{\pi} \pm \frac{\mu B}{E}}$$

where μ is the neutron magnetic moment, E its energy, and B the magnetic induction. It is of interest that the values of the critical angles found (*92*), show that the field acting on the neutron inside the iron is B rather than H.

As the two critical angles correspond to the two alignments of incident neutrons (parallel and antiparallel to B), it is clear that for an incident angle midway between the two, only neutrons of one orientation will be reflected, *i.e.*, the reflected neutrons will be completely polarized. If the mirror is one of magnetized cobalt, the polarization will be complete even if the incident neutrons are not monoenergetic, because the magnetic term in the expression for the critical angle is larger than the nuclear term (*91*). Hughes and Burgy (*92*) have used cobalt mirrors to produce completely polarized neutrons, using reflection at a second cobalt mirror to measure the degree of polarization.

If the coherent scattering amplitude is measured by critical reflection and the total scattering amplitude by transmission, the difference gives the incoherent scattering. If only a single nuclear species is present (no isotopes), the incoherent scattering will be caused

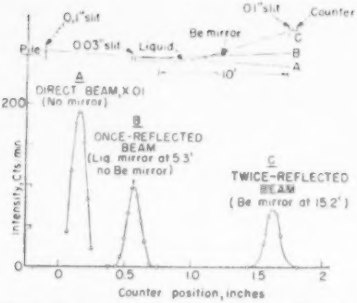

FIG. 17. Apparatus for total reflection of neutrons from liquid mirrors and results for a measurement of the coherent $(n\text{-}p)$ scattering using liquid $C_{12}H_{18}$ (triethylbenzene). Wavelength of the neutrons reflected from the liquid is determined by reflection from a second (Be) mirror

by spin-dependent scattering, in which the scattering amplitude depends on the orientation of the neutron spin with respect to the nuclear spin. In this way information concerning the spin dependence of nuclear forces can be obtained from mirror experiments. The only measurement of this type made so far is that of the coherent neutron-proton scattering (*93*, *94*) in which the critical angle for reflection from a hydrocarbon liquid ($C_{12}H_{18}$) was studied. A diagram of the experiment is shown in Fig. 17, as well as the data for the reflected neutron beams. Because the scattering amplitude of C is positive and that of H negative, the liquid $C_{12}H_{18}$ has an amplitude that is slightly positive, and total reflection is obtained only at very small angles (about 5 minutes for neutrons of wavelength 7 A.U.). The incident angle is measured by the difference in detector position for the direct beam (A) and the beam reflected from the liquid surface (B), while the wavelength is measured by the critical angle for reflection at a second mirror (C), of Be. The free surface of the liquid provides an excellent mirror; no difficulty is experienced from surface vibration. The mirror method in this case provided, in a very simple manner, a measurement that was more accurate than the previous determinations of the coherent (n,p) scattering [para-hydrogen scattering (*95*) and scattering from crystals containing hydrogen (*96*)].

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NEUTRON STANDARDIZATION . . .

. . . will be discussed in part three of "Pile Neutron Research Techniques" which will appear in next month's NUCLEONICS. Besides detailing present neutron standards such as that shown on this month's cover, Dr. Hughes will discuss standardization of: 1. Source strength; 2. Flux; 3. Neutron temperature.

Table for Simplifying Calculations of

Activities Produced by Thermal Neutrons

The formula used to calculate the activity produced in a particular nuclide by thermal neutron irradiation has been modified and is presented in simpler form. Data have been compiled in a table for use with the exponential curve.

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WHEN VARIOUS MATERIALS are to be bombarded by thermal neutrons in a pile or cyclotron, it is often desirable to have an estimate of the activity which may be expected after a given irradiation time at a known flux. The calculation is straightforward and, where only a few items are concerned, it is not exceedingly tedious. However, where these calculations have to be made regularly or where many calculations have to be made in a short time, it is expedient to simplify the calculation.

Such efforts have already been made by others: Eastwood (*1*) has devised a circular slide rule, and, more recently, Cisar (*2*) has constructed a nomograph for the same purpose. In these, a table of cross sections and half-lives must be consulted. Also, both the Eastwood slide rule and the Cisar nomograph involve the weight of the parent nuclide rather than the weight of the parent element. In practice, a given weight of element is irradiated. A separate calculation must be made to determine the weight of the parent nuclide before these devices can be used.

In this laboratory a tabulation has been prepared which includes the percentage abundance factor for the various isotopes of each element, and is thus based on the weight of the parent element. The calculations can therefore be made with nothing more than the use of an ordinary slide rule.

Method of Simplification

The activity produced in a given nuclide by thermal neutrons is

$$A_t = (\sigma f N k)(1 - e^{-0.693t/T})e^{-0.693\theta/T} \quad (1)$$

where A_t = activity of the radionuclide in the target in disintegrations per second after it has been removed from the flux for a period θ.
σ = activation cross section in cm^2
f = neutron flux in neutrons per cm^2/sec.
N = number of atoms of the element in the target from which the radionuclide is formed.
k = relative abundance of the isotope from which the radionuclide is formed.
t = time of irradiation.
θ = time of decay.
T = half-life of radionuclide formed.

The usual procedure in making this calculation is to evaluate the terms in

the parentheses by separate operations. The product (σfNk) in Eq. 1 is the activity obtainable by an infinitely long irradiation period and is called the saturation activity. In most cases irradiation for periods that are greater than ten half-lives will suffice to produce saturation.

The saturation activity of any nuclide, as described above, will be characteristic for any given weight of the target element that is activated in a given flux, since the expression includes the relative abundance of the parent isotope. Therefore, it appears logical, as a step towards simplification in calculating saturation activities, to have a prepared table based on fixed weight and flux values.

For convenience, the table presented in this paper is based on 1 gm of element being irradiated in a flux of 10^9 neutrons per cm^2 per sec. The product (σfNk) is, then, the specific saturation activity of any particular radionuclide, and is designated A_s in the table.

In any given problem, if the flux differs from 10^9 neutrons per cm^2 per sec, the correct value may be obtained by multiplying by a suitable factor of proportionality. The corrected value of A_s for a particular experiment is simply

$$A_s' = \frac{f}{10^9} W A_s \qquad (2)$$

where W is the weight of the element in the sample.

In Eq. 1 $(1 - e^{-0.693t/T})$ is the growth factor for the activity produced. By expanding the exponential it can be simplified

$$1 - e^{-0.693t/T} \approx 0.693t/T \qquad (3)$$

provided that t/T is small, say less than 0.15. Consequently, if t is less than about 15% of the half-life, $0.693t/T$ may be substituted for $(1 - e^{-0.693t/T})$ without incurring an appreciable error, *i.e.*, an error less than the probable error in the known cross sections.

To evaluate growth and decay factors in Eq. 1 when $t/T > 0.15$, the table is supplemented by a graph (pg. 63). The growth factor, $(1 - e^{-0.693t/T})$, has been plotted as a function of t/T, and the decay factor, $e^{-0.693\theta/T}$, as a function of θ/T. Although this curve suffers from lack of accuracy at its extremities, it has been found to be eminently useful in most cases.

In general, Eq. 1 may be written

$$A_t = A_s(1 - e^{-0.693t/T})e^{-0.693\theta/T} \qquad (4)$$

As a special case, where t is known to be less than 15% of T, a further simplification can be made.

$$A_t = A_s\left(\frac{0.693t}{T}\right) e^{-0.693\theta/T}$$
$$= A_s\lambda t e^{-0.693\theta/T} \qquad (5)$$

The values of $A_s\lambda$ can be found in the table and $e^{-0.693\theta/T}$ is most easily obtained from the graph.

In cases where t is greater than 15% of T, only the value A_s can be taken from the table; $(1 - e^{-0.693t/T})$ and $e^{-0.693\theta/T}$ must be obtained from the graph.

The Table (pages 56–61)

The data from which the following table has been compiled have been taken from two of the most recent publications of nuclear constants (*3*, *4*). Additional data have also been included since the values of some of the fundamental information, notably the data on cross sections, are continually changing with increased accuracy of measuring techniques, and thus an estimate of the value of the derived constants can easily be made. The table has been arranged alphabetically according to the symbol of the element. Subscript numbers throughout the table indicate a relatively large probable error.

Text is continued on page 62. The next six pages are devoted to the table of nuclides produced by thermal neutrons. Footnotes to the table appear on page 61.

Table of Nuclides Produced by Thermal Neutrons*

Symbol	Atomic Number Z	Mass of Radio-nuclide A	Half-life T	Cross section (barns) σ	Percent Abundance of Parent Nuclide k	Specific Saturation Activity† (rd) A_s	Decay Constant (sec^{-1}) λ	Activity per gm of element per sec irradiation† (μrd) $A_s\lambda$
A	18	41	1.83 h	1.2	99.61	18.	1.05×10^{-4}	1.9×10^{3}
Ag	47	108	2.3 m	3_0.	51.3_5	8_7.	5.0×10^{-3}	$4._4 \times 10^{5}$
		110	$24._2$ s	9_6.	48.6_5	25_7.	$2.8_6 \times 10^{-2}$	$7._4 \times 10^{6}$
		110	27_0. d	2.3	48.6_5	6.2	$2.9_7 \times 10^{-8}$	1.8×10^{-1}
Al	13	28	2.4 m	0.18	100.0	4.0	4.8×10^{-3}	1.9×10^{4}
As	33	76	26.8 h	4.3	100.0	35.	7.18×10^{-6}	2.5×10^{2}
Au	79	198	2.69 d	96.	100.0	29_3.	2.98×10^{-6}	8.6×10^{2}
B	5	12	0.027 s	0.05‡	$81._{17}$	2.2	2.6×10	††
Ba	56	131	11.7 d	2_4.	0.101	$0._{11}$	6.85×10^{-7}	$7._7 \times 10^{-2}$
		139	85 m	$0._{51}$	$71._6$	1.6	1.4×10^{-4}	2.2×10^{2}
Be	4	10	2.7×10^{6} y	0.01	100.0	$0._7$	8.1×10^{-15}	$5._4 \times 10^{-9}$
Bi	83	210	5.0 d	0.015	100.0	0.043	1.6×10^{-6}	$6._9 \times 10^{-2}$
Br	35	80	4.4 h	$3._0$	$50._{52}$	1_2.	4.4×10^{-5}	5.1×10^{2}
		80	18 m	$8._9$	$50._{52}$	3_4.	6.4×10^{-4}	$2._2 \times 10^{4}$
		82	35 h	$2._3$	$49._{48}$	$8._5$	5.5×10^{-6}	$4._7 \times 10$
C	6	14	5.7×10^{3} y	0.1‡	1.12	$0._{05}$	3.9×10^{-12}	$2._0 \times 10^{-7}$
		14**	5.7×10^{3} y	1.7‡	99.62(N)	$72._5$	3.9×10^{-12}	2.8×10^{-4}
Ca	20	41	10 d‡	0.0002‡	96.96	2.9×10^{-3}	8.0×10^{-7}	2.3×10^{-3}
		45	152 d	0.63‡	2.06	0.18	5.28×10^{-8}	9.4×10^{-3}
		49	2.5 h	0.2	$0._{185}$	$4._7 \times 10^{-3}$	7.7×10^{-5}	$3._6 \times 10^{-}$
		49	30 m	$0._{55}$	$0._{185}$	$0._{013}$	3.9×10^{-4}	5.0
Cd	48	107	6.7 h	1.	1.21	$0._{069}$	2.9×10^{-5}	$2._0$
		111	$48._6$ m	0.2	$12._{39}$	$0._{14}$	$2._{38} \times 10^{-4}$	$3._2 \times 10$
		115	43 d	0.14	$28._{86}$	0.21	1.9×10^{-7}	4.0×10^{-2}
		115	2.33 d	1.1	$28._{86}$	1.7	3.45×10^{-6}	5.8
		117	$2._{83}$ h	1.4	$7._{58}$	0.55	$6._{85} \times 10^{-5}$	3.7×10
Ce	58	141	28 d	$0._{95}$	$88._{48}$	$3._6$	2.9×10^{-7}	1.0

Ce	58	141	28 d	0.9_5	88.4_8	$3._6$	2.9×10^{-7}	1.0	
		143	33 h	0.3_1	11.0_7	0.1_5	5.8×10^{-6}	$8._4$	
Cl	17	36	2×10^6 y	53.	75.4	69_0.	$1. \times 10^{-14}$	$6._9 \times 10^{-6}$	
		38	$37._5$ m	0.6	24.6	$2._4$	$3.0_8 \times 10^{-4}$	$7._4 \times 10^2$	
Co	27	60	$5._3$ y	22.5	100.0	230.	$4._2 \times 10^{-9}$	$9._7 \times 10^{-1}$	
		60	10.7 m	0.73	100.0	7.4	1.08×10^{-3}	8.0×10^3	
Cr	24	51	$26._5$ d	16.2	4.31	8.4	$3.0_3 \times 10^{-7}$	2.6	
		55	1.3 h	0.006	2.38	$1._6 \times 10^{-3}$	1.5×10^{-4}	$2._4 \times 10^{-1}$	
Cs	55	134	3.1_5 h	0.016	100.0	0.072	$6.1_1 \times 10^{-5}$	4.4	
		134	2.3 y	25.6	100.0	116.	9.6×10^{-9}	1.1	
Cu	29	64	12.8_8 h	4.3	69.1	28	1.5×10^{-5}	4.2×10^2	
		66	4.3_4 m	2.1	30.9	6.0	$2.6_6 \times 10^{-5}$	1.6×10^4	
Dy	66	165	1.2_5 m	27_{00}.	27.3	27_{10}.	$9.2_4 \times 10^{-3}$	2.5×10^7	
		165	2.4_2 h	27_{00}.	27.3	27_{10}.	$7.9_5 \times 10^{-5}$	2.2×10^5	
Er	68	171	7.5 h	7.	14.2	$3._5$	2.6×10^{-5}	9.1×10	
Eu	63	152	9.2 h	15_{30}.	47.7_7	29_{20}.	2.1×10^{-5}	6.1×10^4	
		152	$5._3$ y	25_{00}.	47.7_7	47_{70}.	4.2×10^{-9}	2.0×10	
		154	5–20 y	10^3	52.2_3	2_{000}.	$4\text{–}1 \times 10^{-9}$	8–2	
F	9	20	12 s	0.01	100.0	0.32	5.8×10^{-2}	1.8×10^4	
Fe	26	55	4 y	$2._1$	5.8_4	$1._4$	$6. \times 10^{-9}$	$8._4 \times 10^{-3}$	
		59	46 d	0.32	0.31	0.01	1.7×10^{-7}	1.8×10^{-3}	
Ga	31	70	20.5 m	1.5	60.2	7.9	5.63×10^{-4}	4.4×10^3	
		72	14.2_5 h	3.4	39.8	11.	1.34×10^{-5}	1.5×10^2	
Gd	64	153	2×10^2 d	125.	0.21	1.0	$4. \times 10^{-8}$	$4._2 \times 10^{-2}$	
		159	17.9 h	1.1	24.7_5	1.0	1.08×10^{-5}	1.1×10	
		161	3.6_2 m	0.17	21.7_7	0.14	$3.1_8 \times 10^{-3}$	4.4×10^2	
Ge	32	71	11.4 d	0.45	20.5_5	0.8	7.0×10^{-7}	5.6×10^{-1}	
		71	40 h‡	0.073‡	21.2‡	0.13	4.8×10^{-6}	6.4×10^{-1}	
		75	89 m	0.6_0	36.7_4	$1._8$	1.3×10^{-4}	2.3×10^2	
		77	12 h	0.08_5	7.6_7	0.05_2	1.6×10^{-5}	8.3×10^{-1}	
		77	59 s	0.09_5	7.6_7	0.05_8	1.2×10^{-2}	6.8×10^2	
H	1	3	10.7 y	$6._8 \times 10^{-4}$	0.016	$3._1 \times 10^{-5}$	2.06×10^{-9}	$6._5 \times 10^{-8}$	
		3§	10.7 y	86_0.	7.5(Li)	65_{00}.	2.06×10^{-9}	1.3×10	
		3••	10.7 y	5×10^3	1.2×10^{-4}(He)	1.2	2.06×10^{-9}	2.4_7	

Table of Nuclides Produced by Thermal Neutrons—(Continued)

Symbol	*Atomic Number Z*	*Mass of Radio-nuclide A*	*Half-life T*	*Cross section (barns) σ*	*Percent Abundance of Parent Nuclide k*	*Specific Saturation Activity† (rd) A_s*	*Decay Constant (sec^{-1}) λ*	*Activity per gm of element per sec irradiation† (μrd) $A_s\lambda$*
Hf	72	181	46 d	10.‡	35.1_1	$11._7$	1.7×10^{-7}	2.0
Hg	80	197	64 h	3.1×10^3	0.15	14.	3.0×10^{-6}	4.3×10
		201	43 m	$<60.$	23.3	42.	2.7×10^{-4}	1.1×10^4
		203	48 d	2.4	29.6	2.1	1.7×10^{-7}	3.5×10^{-1}
		205	5.5 m	0.34	6.7	0.06_7	2.1×10^{-3}	1.4×10^2
Ho	67	166	27.2 h	$6_7.$	100.0	$2_{18}.$	7.07×10^{-6}	$1._7 \times 10^3$
I	53	128	24.9_8 m	6.8	100.0	32.	$4.6_2 \times 10^{-4}$	1.5×10^4
In	49	114	48 d	$6_1.$	4.23	$1_4.$	1.7×10^{-7}	$2._3$
		114	72 s	2.	4.23	0.4_5	9.6×10^{-3}	4.3×10^1
		116	53.9_3 m	$5_6.$	95.77	$28_0.$	2.14×10^{-4}	6.0×10^4
		116	13 s	$15_7.$	95.77	$78_4.$	5.3×10^{-2}	$4._2 \times 10^7$
Ir	77	192	1.5 m	260.	38.5	316.	7.7×10^{-3}	2.4×10^6
		194	19.0 h	130‡	61.5	249.	1.0×10^{-5}	2.5×10^3
K	19	42	12.4_4 h	1.0	6.7	0.98	1.6×10^{-5}	1.5×10
Kr	36	79	34 h	0.27	0.34_4	0.007_2	5.7×10^{-6}	$4._1 \times 10^{-2}$
		85	4.5 h	0.96	56.9_8	3.9	4.3×10^{-5}	1.7×10
		85	9.4 y	0.06	56.9_9	0.2_4	$2._3 \times 10^{-9}$	5.7×10^{-4}
		87	74 m	0.06_4	17.4_3	0.07_8	1.6×10^{-4}	1.2×10
La	57	140	40.0 h	9.	99.9_1	$3_9.$	4.8×10^{-6}	$1._9 \times 10^2$
Li	3	8	0.88 s	0.033	92.5	2.6	7.9×10^{-1}	††
Lu	71	176	3.7 h	$3_0.$	97.5	$1_{00}.$	5.2×10^{-5}	$5._2 \times 10^3$
		177	6.6 d	$3._2 \times 10^3$	2.5	$2_{72}.$	1.2×10^{-6}	$3._3 \times 10^2$
Mg	12	27	10.2 m	$4._8 \times 10^{-2}$	11.2_9	0.1_3	1.1×10^{-3}	$1._4 \times 10^2$
Mn	25	56	2.59 h	$12._8$	100.0	$14_0.$	7.43×10^{-5}	1.0×10^1

Mo	42	93	6.7 h	0.2	15.8_6	0.2_1	2.9×10^{-5}	$6._0$
		99	67 h	0.3	23.7_5	0.4_4	2.9×10^{-6}	$1._3$
		101	14.6 m	0.2	9.6_2	0.1_2	7.9×10^{-4}	$9._5 \times 10$
N	7	16	7.35 s	2×10^{-5}	0.38	$3._0 \times 10^{-6}$	9.4×10^{-2}	$2._8 \times 10^{-1}$
Na	11	24	14.8 h	0.5	100.0	$1_3.$	1.3×10^{-5}	$1._7 \times 10^{2}$
Nb	41	94	6.6 m	1.2	100.0	7.8	1.8×10^{-3}	1.4×10^{4}
Nd	60	147	11.0 d	1.5	17.1_8	1.1	7.3×10^{-7}	7.8×10^{-1}
		149	1.7 h	2.4	5.7_2	0.56	1.1×10^{-4}	6.3×10
Ni	28	59	5×10^{4} y	4.2	67.4	29.	4.4×10^{-13}	1.3×10^{-5}
		63	30_0 y	15.	3.8	5.5	7.3×10^{-11}	4.1×10^{-4}
		65	2.5_0 h	2.6	0.88	0.22	7.7×10^{-5}	1.7×10
O	8	19	29 s	2.2×10^{-4}	0.20	1.5×10^{-5}	2.4×10^{-2}	3.5×10^{-1}
Os	76	191	15 d	3.4	26.4	2.8	5.4×10^{-7}	1.5
		193	32 h	3.9	41.0	5.0	6.0×10^{-6}	3.0×10
P	15	32	14.3 d	0.2	100.0	$3._9$	5.6×10^{-7}	$2._2$
Pb	82	209	3.3_2 h	4.5×10^{-4}‡	52.3	6.8×10^{-4}	5.8×10^{-5}	3.9×10^{-2}
Pd	46	109	13.2 h	$12._1$	26.8	$18._1$	1.46×10^{-5}	$2.6_4 \times 10^{2}$
		111	26 m	0.39	13.5	0.29	4.4×10^{-4}	1.3×10^{2}
Pr	59	142	19.3 h	11.	100.0	47.	9.97×10^{-6}	4.7×10^{2}
Pt	78	197	18 h	1.1	25.4	0.86	1.1×10^{-5}	9.2
		197	3.3 d	4.5	25.4	3.5	2.4×10^{-6}	8.4×10
		199	31 m	3.9	7.2	0.85	3.7×10^{-4}	3.2×10^{2}
Rb	37	86	$19._5$ d	0.7_2	72.8	$3._7$	$4.1_2 \times 10^{-7}$	$1._5$
		88	17.8 m	0.12	27.2	0.23	6.49×10^{-4}	1.5×10^{2}
Re	75	186	91 h	$10_1.$	37.0_7	$12_0.$	2.1×10^{-6}	2.5×10^{2}
		188	18 h	75.	62.9_3	$15_0.$	1.1×10^{-5}	1.6×10^{3}
Rh	45	104	4.4 m	$11._8$	100.0	69.	2.6×10^{-3}	1.8×10^{5}
		104	42 s	$13_7.$	100.0	$80_0.$	1.7×10^{-2}	1.3×10^{7}
Ru	44	97	2.8 d	0.01	6.	0.003_8	2.9×10^{-6}	$1._1 \times 10^{-2}$
		103	$41._0$ d	1.2	31.	2.2	$1.9_6 \times 10^{-7}$	4.3×10^{-1}
		105	4.5 h	0.67	18.	0.70	4.3×10^{-5}	3.0×10
S	16	35	$81._1$ d	0.26	4.15	0.19	$9.8_8 \times 10^{-8}$	1.9×10^{-2}
		37	5.0_4 m	0.14	0.016	3.7×10^{-4}	$2.2_9 \times 10^{-3}$	8.5×10^{-1}

Table of Nuclides Produced by Thermal Neutrons—(Continued)

Symbol	*Atomic Number* Z	*Mass of Radio-nuclide* A	*Half-life* T	*Cross section (barns)* σ	*Percent Abundance of Parent Nuclide* k	*Specific Saturation Activity†* (rd) A_s	*Decay Constant* (sec^{-1}) λ	*Activity per gm of element per sec irradiation†* (μrd) $A_s\lambda$
Sb	51	122	2.8 d	$6._8$	57.25	1_9.	2.9×10^{-6}	$5._5 \times 10$
		124	21 m	0.03	42.7_5	0.06	5.5×10^{-4}	3.5×10
		124	60 d	2.5	42.7_5	5.2	1.3×10^{-7}	7.0×10^{-1}
Sc	21	46	20 s	~ 15.	100.0	20_0.	3.5×10^{-2}	7.0×10^{0}
		46	85 d	22.	100.0	29_4.	9.4×10^{-8}	2.8×10
Se	34	75	127 d	24.	0.87	1.7	6.32×10^{-8}	1.1×10^{-1}
		81	58 m	0.03	49.8_2	0.11	2.0×10^{-4}	2.2×10
		81	18 m	0.5	49.8_2	$1._9$	6.4×10^{-4}	$1._2 \times 10^{3}$
		83	67 s	0.04_7	9.1_9	0.03_2	1.0×10^{-2}	3.3×10^{2}
		83	25 m	0.004	9.1_9	0.002_7	4.6×10^{-4}	1.2
Si	14	31	2.8_3 h	0.12	3.05	0.07_4	$6.8_0 \times 10^{-5}$	5.0
Sm	62	153	$47._0$ h	28_0.	26.6_8	29_4.	$4.1_0 \times 10^{-6}$	1.2×10^{3}
		155	25 m	6.	22.5_3	$5._3$	4.6×10^{-4}	$2._4 \times 10^{3}$
Sn	50	113	105 d	1.1	0.90	0.05_3	7.7×10^{-8}	4.0×10^{-3}
		123	47 m	0.16	4.7_8	0.03_8	2.5×10^{-4}	9.3
		125	9.5 m	0.5_7	6.11	0.1_7	1.2×10^{-3}	$2._1 \times 10^{2}$
Sr	38	87	2.7 h	1.3	9.8_6	0.90	7.1×10^{-5}	6.4×10
		89	55 d	0.005	82.5_6	0.028	1.5×10^{-7}	4.1×10^{-3}
Ta	73	182	113 d	20.6	100.0	68.	7.10×10^{-8}	4.9
		182	16.2 m	0.034	100.0	0.11	7.12×10^{-4}	8.0×10
Tb	65	160	3.9 h	11.	100.0	42.	5.0×10^{-5}	2.1×10^{3}
		160	75 d	22.	100.0	84.	1.1×10^{-7}	9.1

Te	52	125	58 d	5.	4.61	1.1_1	1.4×10^{-7}	1.6×10^{-1}
		127	90 d	0.073	18.7_1	0.066	8.9×10^{-8}	5.8×10^{-3}
		127	9.3 h	0.78	18.7_1	0.70	2.1×10^{-5}	1.4×10
		129	32 d	0.015	31.7_9	0.022	2.5×10^{-7}	5.6×10^{-3}
		129	72 m	0.13	31.7_9	0.20	1.6×10^{-4}	3.1×10
		131	30 h	0.008	34.4_9	0.013	6.4×10^{-6}	8.2×10^{-2}
		131	25 m	0.22	34.4_9	0.35	4.6×10^{-4}	1.6×10^{2}
Ti	22	51	6 m	0.14	5.34	0.09	1.9×10^{-3}	1.7×10^{2}
Tl	81	204	2.7 y	7.5	29.2	6.7	8.1×10^{-9}	5.4×10^{-2}
		206	4.23 m	0.11	70.5_4	0.23	2.73×10^{-3}	6.2×10^{2}
Tm	69	170	12_7 d	11_8.	100.0	42_0.	6.3×10^{-8}	2.6×10
V	23	52	37.4 m	5.	100.0	5_9.	3.1×10^{-4}	1.8×10^{4}
W	74	185	74 d	2.1	30.6	2.1	1.1×10^{-7}	2.3×10^{-1}
		187	24.1 h	37.2	28.4	34.	$7.9_8 \times 10^{-6}$	2.7×10^{2}
Xe	54	133	5.27 d	0.2	26.9_4	0.2_5	1.5×10^{-6}	3.8×10^{-1}
		135	12 m	0.2	10.5_8	0.1	9.6×10^{-4}	9.1×10
		137	3.9 m	0.15	8.9_4	0.05_9	3.0×10^{-3}	1.8×10^{2}
Y	39	90	62 h	1.2	100.0	8.1	3.1×10^{-6}	2.5×10
Yb	70	169	33 d	1.8×10^{4}	0.14	90.	2.4×10^{-7}	2.2×10
		175	4.1 d	50.	31.8	55.	2.0×10^{-6}	1.1×10^{2}
		177	2.0 h	5.	12.7	2.2	9.6×10^{-5}	2.1×10^{2}
Zn	30	65	25_0 d	0.5	48.8_9	2.3	$3.2_1 \times 10^{-8}$	7.4×10^{-2}
		69	13.8 h	0.09	18.5_6	0.15	1.39×10^{-5}	2.1
		69	57 m	0.9	18.5_6	1.5	2.0×10^{-4}	3.0×10^{2}
		71	2.2 m	0.09	0.62	0.00_5	5.3×10^{-3}	2.5×10
Zr	40	93	40 y‡	0.27	17.1_1	0.30	5.5×10^{-10}	1.6×10^{-4}
		95	65 d	0.1	17.4_0	0.1_1	1.2×10^{-7}	1.4×10^{-2}
		97	17.0 h	0.2_9	2.80	0.0_5	1.13×10^{-5}	5.8×10^{-1}

* The basic data in this table is taken essentially from reference *3*.
† Cols. 7 and 9 based on neutron flux of 10^9 $n/cm^2/sec$.
‡ Data taken from reference *4*.
§ (n,α) reaction.
** (n,p) reaction.
†† 1 sec $\gg 0.15T$.

Examples

Problem 1. How long must a 3-gm gold foil be irradiated in a flux of 10^8 neutrons/cm²/sec to attain an activity of 8×10^7 disintegrations per second? What is the activity 3 days after removal of the foil from the flux?

Solution. A_t in Eq. 4 is 80 rd. A_s from the table is 293 rd. Since this value is based on 1 gm of element and a flux of 10^9 neutrons/cm²/sec, 293 must be multiplied by 3×10^{-1} to correct for weight and flux. As it is desired to know the activity upon removal from the flux, the decay factor $e^{-0.693t/T}$ is dropped from Eq. 4. Hence

$$80 = 293 \times 3 \times 10^{-1}(1 - e^{-0.693t/T})$$
$$1 - e^{-0.693t/T} = 0.92$$

From the graph, 0.92 corresponds to a value of $t/T = 3.65$, and, since T is 2.69 days, t is 9.8 days.

To obtain the activity of the foil 3 days after removal from the flux, the total activity of 80 need only be multiplied by the decay factor $e^{-0.693\theta/T}$, obtained from the curve. θ/T for this decay period is $(3/2.69) = 1.12$, and this corresponds to 0.465 on the graph. Thus, the activity after 3 days will be

$$A_t = 80 \times 0.465 = 37.2 \text{ rd}$$

Problem 2. A 0.5 gm button of wolfram is placed in a flux of 10^{11} neutrons/cm²/sec for 3 days. What is the activity due to the 24-hour and the 74-day radionuclides which are produced upon removal from the flux?

Solution. *24-h wolfram*—The ratio t/T is $(72/24.1) = 2.99$. This corresponds to a growth factor of 0.885 on the graph. A_s from the table is 34 rd. This has to be corrected for the weight of the wolfram button and the neutron flux. Thus, substituting in Eq. 4,

$$A_t = 34 \times 0.5 \times 10^2 \times 0.885 = 1{,}500 \text{ rd}$$

74-d wolfram—The ratio of t/T is less than 0.15 in this case, and, therefore, $A_s\lambda$ can be used directly. $A_s\lambda$ from the table is 2.3×10^{-1} μrd/gm/sec. Therefore

$$A_t = A_s\lambda t = 2.3 \times 10^{-1} \times 0.5 \times 10^2 \times (3 \times 24 \times 60 \times 60) = 298 \times 10^3 \ \mu\text{rd}$$

Problem 3. What is the ratio of the activities due to sodium and potassium in a rock specimen immediately upon removal of the specimen from the pile? Assume the specimen has been irradiated for a period of 1 day and that it contains 5% sodium and 2% potassium by weight.

Solution. From the table and the graph we obtain

for sodium:

$A_s = 13$, or 0.05×13 (corrected)

$t/T = 24/14.8 = 1.62$ which corresponds to

$(1 - e^{-0.693t/T}) = 0.665$

for potassium:

$A_s = 0.98$, or 0.02×0.98 (corrected)

$t/T = 24/12.4 = 1.94$ which corresponds to

$(1 - e^{-0.693t/T}) = 0.745$

Neglecting the decay factor in Eq. 4 we have for the ratio of activities

$$\frac{A_{Na}}{A_K} = \frac{0.05 \times 13 \times 0.665}{0.02 \times 0.98 \times 0.745} = 29.6$$

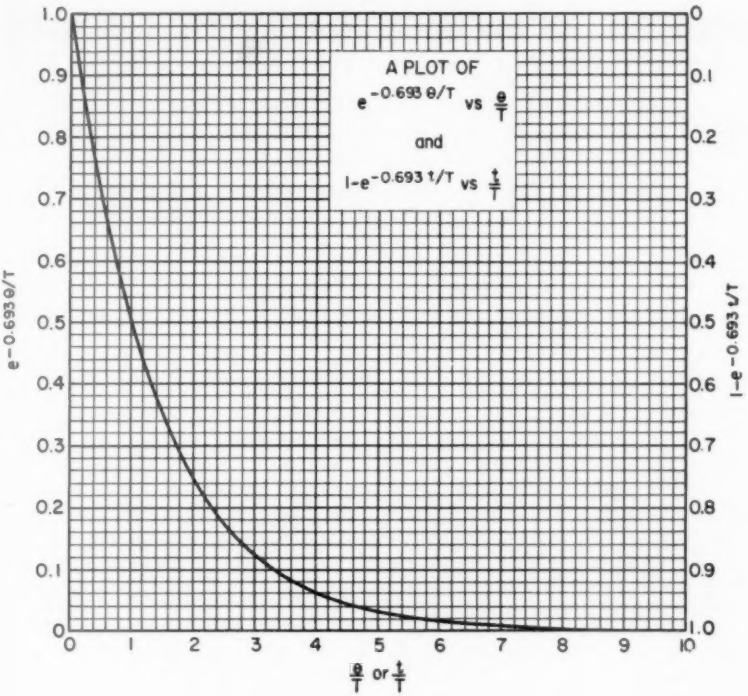
If the irradiation time in this example had been two weeks instead of 1 day, both nuclides would reach saturation activity, and the ratio would be simply that of their corrected A_s values. Thus

$$\frac{A_{Na}}{A_K} = \frac{0.05 \times 13}{0.02 \times 0.98} = 33.2$$

Conclusion

The method of calculation described has been found useful for certain types of work of which examples have been given. It has also been found useful in making a rapid comparison of the activities which might be expected from several different elements.

For instance, suppose it is desired to know which of the three elements, cobalt, nickel, or vanadium is most easily activated by thermal neutrons. If reference is made to a cross-section table only, the values may be misleading unless properly interpreted by a suitable comparison of half-lives and abundances. In this table all the variables have been combined and the desired information can be obtained directly from the values of $A_s\lambda$, the



activity produced per gm per sec, under the stated conditions. Hence, it is easily seen that, under similar circumstances of irradiation, vanadium is most easily activated even though the cross section of one of the cobalt isotopes is nearly five times and one of the nickel isotopes three times that of vanadium.

* * *

The authors are grateful to Professor A. M. Gaudin for commenting on this table, and to various members of the staff for their stimulating discussions. This project was sponsored by the Division of Research, Atomic Energy Commission, and carried out in the Richards Mineral Engineering Laboratories, Massachusetts Institute of Technology.

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NEUTRON PRODUCTION BY COMPLETE ABSORPTION

Calculations of neutron yield per high-energy photon completely absorbed in an absorber of high atomic number are outlined, with indications of their usefulness in cosmic-ray research, studies of photonuclear reactions, and neutron-background evaluation in electron-accelerator experiments.

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WHEN a high-energy photon strikes an absorber many radiation lengths thick, the incident photon generates a shower containing many photons of lower energy. Some of the lower-energy photons in the shower generate neutrons by photonuclear reactions in the absorber. To illustrate this reaction in lead, for example, see Fig. 1.

In this paper, an approximate calculation is made of the yield of neutrons produced per high-energy photon completely absorbed in an absorber of high atomic number. This calculation might apply to: *a*) neutron-background calculations in experiments with electron accelerators; *b*) cosmic-ray experiments like those made by V. T. Cocconi (*1*); *c*) analysis of the source of cosmic-ray neutrons in the atmosphere, such as that by Fujimoto, Hayakawa, and Yamaguchi (*2*); *d*) studies of photonuclear reactions, similar to those of Strauch and Eyges (*3*).

At a depth of t radiation lengths, the number of photons of energy W in a shower created by an incident photon of energy W_0 will be denoted by $\gamma(W_0,W,t)$, following Rossi and Greisen's notation (*4*). These photons of energy W produce neutrons with nuclear cross section $\sigma(W)$, and average multiplicity $\nu(W)$. The yield of neutrons per incident high-energy photon completely absorbed is then

$$Y = \int_0^{W_0}\int_0^{\infty} N\nu(W)\sigma(W)\gamma(W_0,W,t)\,dt\,dW = N\int_0^{W_0}\nu(W)\sigma(W)z_\gamma(W_0,W)\,dW \quad (1)$$

Here N is the number of nuclei per cm^2 of a length of 1 radiation length ($\frac{1}{2}$ cm of lead) or 1.7×10^{22} for lead. The track length $z_\gamma(W_0,W)$ is the total distance traveled by photons of energy between W and $W+dW$ in a shower generated by an incident photon of energy W_0.

For W much larger than the critical energy of shower theory (7 Mev for lead), but much less than W_0, we may use approximation A of Rossi and Greisen (*4*). Their equation 2.45 states:

$$z_\gamma(W_0,W) = \int_0^{\infty}\gamma(W_0,W,t)\,dt = 0.572W_0/W^2 \quad (2)$$

Approximation A is inaccurate in two significant respects: 1) its use of the asymptotic value for pair-production cross sections, valid for high-energy photons; and 2) its neglect of energy loss by electrons by ionization.

Richards and Nordheim (*5*) give numerical results for the track lengths in lead, or in air, which are not based

on these approximations. For lead and other heavy absorbers, the use of asymptotic pair-production cross sections in approximation A reduces the track length below the results of Richards and Nordheim. For air, on the other hand, at the photon energies with which we are concerned, the collision loss of electrons is the predominant effect; therefore, approximation A gives too large a track length for this case.

Since the cross sections for photonuclear reactions for heavy nuclei appear to be appreciable only for photon energies between 10 and 30 Mev, *i.e.*, for energies somewhat above the critical energy of shower theory, we shall approximate Richards' and Nordheim's results, for incident photons of high energy absorbed in lead, by

$$z_\gamma(W_0,W) = 1.4 \times 0.572 W_0/W^2 \quad (3)$$

This agrees with their numerical results within 10% for the energy range of W from 10 to 30 Mev. See Fig. 2. For the track length in air, for photons of energy between 15 and 50 Mev (*i.e.*, for energies somewhat less than the critical energy for air), the factor in approximating Richards' and Nordheim's results is only 0.4, instead of 1.4, for the case of lead.

Measurements of the absolute cross section (*6*), relative photonuclear cross sections (*7*), and energy dependence of the cross sections (*8*) were made with the 100-Mev General Electric betatron. Photonuclear cross sections have been calculated by the author and Bethe (*9*). In the latter paper, the G.E. experiments are discussed, and it is shown that these calculations are in fair agreement with the experimental results. The relevant results are quoted here.

First, the average multiplicity $\nu(W)$ of neutrons produced per photonuclear reaction is rather close to unity (*7*). Second, a reasonable extrapolation, based on theory, of the G.E. results gives for lead nuclei

$$\int_0^\infty \sigma \, dW/W = 0.3 \text{ barns} \quad (4)$$

For calculation of the neutron yield from complete absorption of high-energy photons, we need a different integrated photonuclear cross section:

$$\int_0^{W_0} \sigma \, dW/W^2 \cong \int_0^\infty \sigma \, dW/W^2 = (1/W_a) \int_0^\infty \sigma \, dW/W \quad (5)$$

This equation defines W_a as a sort of harmonic average energy for the photons absorbed; it is weighted in favor of low-energy photons. On the basis of insufficient evidence, a guess of 20 Mev is made for the value of W_a for lead nuclei. (Later, a method is suggested for measuring the approximate value of W_a.)

Using Eqs. 3, 4, and 5 in Eq. 1 for the neutron yield Y by complete absorp-

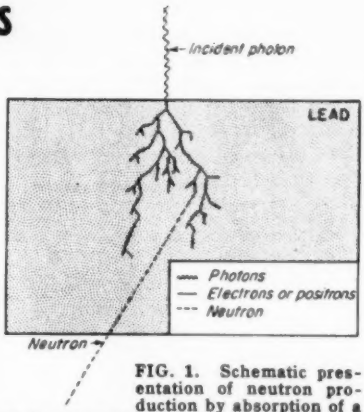

FIG. 1. Schematic presentation of neutron production by absorption of a high-energy photon. Angular divergence of the shower has been exaggerated. Penetration of the shower into the lead has been drawn roughly to scale for an incident photon of 300 Mev. Shown is the one lucky case—a 6% chance—when one photon in the shower produces a neutron by a photonuclear reaction

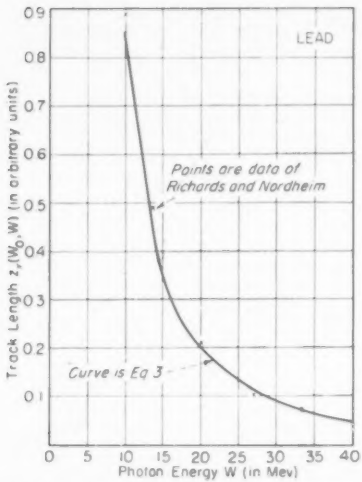

FIG. 2. Track length vs photon energy

tion of a high-energy photon in lead, we have

$$Y = N(1.4 \times 0.572 W_0/W_a) \int_0^\infty \sigma \, dW/W = 2 \times 10^{-2} W_0 \quad (6)$$

where W_0 is expressed in units of 100 Mev. This calculated yield should be accurate within a factor of 2.

The same neutron yield is found if an incident high-energy electron of energy $E_0 = W_0$ initiates a shower that is completely absorbed, since the track length for low-energy photons in a shower does not depend on whether the initiating particle is an electron or a photon (4).

It is of interest to consider how the neutron yield depends on the atomic number Z of the absorber. The number of nuclei per radiation length, N, varies approximately as $1/Z^2$, while the integrated photonuclear cross sections vary approximately as Z.* The variation of the neutron yield, however, is less drastic than $1/Z$, since the ratio of the Richards-Nordheim calculated track length to that of Eq. 2 depends on the value of Z. The $1/Z$ dependence for the neutron yield is modified to an approximate $1/Z^{1/2}$ dependence.

If photons or electrons with an energy distribution $f(W_0)$ strike a thick absorber, the neutron yield is proportional to the total energy incident in the form of high-energy photons and electrons:

$$\int_{W_t}^\infty W_0 f(W_0) \, dW_0,$$

where W_t represents a threshold for photonuclear reactions.

Since the photon spectrum from electron accelerators has approximately the bremsstrahlung form, or approximately dW_0/W_0, up to maximum energy W_m, the neutron yield for complete absorption in lead becomes

$$Y = N(1.4 \times 0.572/W_a) \int_{W_t}^{W_m} W_0 \, dW_0/W_0 \int_0^\infty \sigma \, dW/W \quad (7)$$
$$= N(1.4 \times 0.572/W_a)(W_m - W_t) \int_0^\infty \sigma \, dW/W$$

We can compare this with the yield Y' for neutron production in a thin absorber, *i.e.*, an absorber much less than a radiation length in thickness, so that there is no appreciable modification of the photon beam from the accelerator:

$$Y' \cong N' \int_0^\infty \sigma \, dW_0/W_0 \quad (8)$$

Here N' is the number of nuclei per cm² for the thin absorber.

Taking the ratio of the neutron yields in the two cases and solving for the harmonic mean energy for photon absorption W_a, we obtain

$$W_a = (1.4 \times 0.572 Y'N/YN') \times (W_m - W_t) \quad (9)$$

Of course, the factor 1.4 is valid only for lead or neighboring elements, and

* NOTE ADDED IN PROOF: G. C. Baldwin and F. R. Elder [*Phys. Rev.* **78**, 76 (1950)] find that the integrated photonuclear cross section varies roughly as Z^2. This changes our results to: a) Y varies roughly as $Z^{1/2}$; b) Y for lead is increased by a factor of about two.

the whole method is only approximate.

We should point out that one could study either neutron production in the whole absorber, or neutron production in thin foils of a different material, suitably located in the absorber. In the latter case, one can find the total yield of some particular photonuclear reaction by integrating the curve of induced activity vs position of foil in the absorber, as suggested by Strauch and Eyges.

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Existence of Two Subatomic Particles Verified

Two cosmic-ray particles, unobserved since their discovery by G. D. Rochester and C. C. Butler of the University of Manchester, England, in 1947, have been verified by California Institute of Technology scientists. Dr. Carl D. Anderson, who headed a group which included Dr. R. B. Leighton, Dr. E. W. Cowan, A. J. Seriff and C. Hsiao, reported the research to the American Physical Society at the April meeting in Washington, D. C.

Eleven thousand cloud-chamber photographs yielded 30 pictures of one type of particle and four pictures of a second type. The cloud chamber apparatus was controlled by a battery of Geiger counters mounted below an 8-in. thick lead plate; the chamber was tripped only when particles of very high energy penetrated the plate. Mounted on a trailer, the chamber was used for 3,000 observations on the Cal Tech campus and 8,000 observations on White Mountain at an altitude of 10,500 ft.

The first particle, evident in both locations, is a neutral one which breaks down into two others, each of which carries a charge. One of these secondary particles, and possibly both, appears to be one of the mesons.

The mass of the first type of particle is still to be determined. Its mass may range from 500 to 1,000 electron masses, or from 2,200 to 2,500 electron masses, depending upon the identity of the secondary particles.

The second type of particle, of which only four photographs were obtained (on White Mountain), is a charged one which breaks down into two secondary particles, one neutral and one charged. There is not sufficient data to allow computation of its mass.

Including the two new ones, 13 subatomic particles are now known. These include the electron, neutron, proton, positron, five kinds of mesons, the neutrino, and photon.

CROSS SECTIONS

Liquid Scintillation Counters*

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The usefulness of crystal scintillation counters for cosmic ray research has been recognized for some time (*1*). Comprehensive surveys of the properties of various scintillation crystals have been conducted by Kallmann (*2*) and Hofstadter (*3*) and by Jordan and Bell (*4*). However, because of the low counting rates encountered in cosmic ray observations, it is necessary to employ large clear crystals in order to make some of the interesting experiments feasible. In general it is difficult to grow clear crystals of organic compounds (desirable because of the short pulse duration) free of fracture in sizes greater than the order of 50 grams, even with rather elaborate precautions with respect to purity of sample, temperature control of large furnaces, *etc.* Since such limitations do not apply to clear solutions, a program was recently undertaken at Princeton University to investigate the scintillation properties of a series of solutions (*5*).

The first solutions investigated were dibenzyl in ether, and naphthalene in benzene. These combinations were chosen because it was possible to get 7% and 35% by weight, respectively, of solid into solution. The solution was placed in the pyrex container shown in Fig. 1 and viewed with a 1P21 photomultiplier. In all of the experiments to be described, the pulses observed are due to the Compton electrons in the solution arising from the γ-rays of a 1 millicurie Co^{60} source.

With these first solutions it was necessary to use two 1P21's placed at opposite ends of the cell and count only coincidences, since the pulses from the solutions were the same order of magnitude as the photomultiplier noise. By comparing single channel counting rates with coincidence rates, it is possible to measure a figure-of-merit for each solution. On this basis the dibenzyl and naphthalene solutions rate a number 0.15, compared to a figure of 0.9 for a

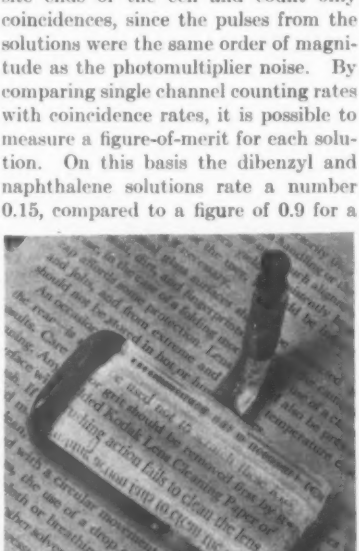

FIG. 1. Pyrex container containing scintillation solution

* Assisted in part by the joint program of the Office of Naval Research and the Atomic Energy Commission. Reproduction, translation, publication, use and disposal in whole or in part by or for the U. S. Government is permitted.

good naphthalene crystal. This figure-of-merit is useful mainly in establishing relative effects and should not be taken as an absolute measure of the efficiency of the sample. With slight variations in geometry and photomultiplier characteristics, it has proved reproducible to the order of 4%.

A series of solutions and liquids were then investigated, including those listed in the table. The terphenyl solutions were selected for further study. With these solutions it is possible to dispense with the coincidence technique and view the pulses directly by suitably amplifying the signal from an end-window photomultiplier and observing the pulse on an oscilloscope. The terphenyl pulse sizes are observed to be a little less than one half those from an anthracene crystal used for comparison, and are at least as fast as the amplifier characteristics (rise time 0.02 μsec, decay time 0.04 μsec).

The terphenyl used in these observations was commercially obtained but further purified in the laboratory. Similar observations using the commercial grade terphenyl directly indicate that the pulse heights and figure-of-merit are not significantly less for these than for the specially purified specimens. The effect of concentration has been investigated and the results are shown in Fig. 2. These observations involve pure terphenyl in xylene, and indicate that a figure-of-merit of 0.3 is obtained for concentrations by weight as little as 3 parts in 100,000. The figure for xylene alone is 0.08.

With a view toward exploiting the particular advantages of solutions for cosmic ray work, *i.e.*, the ease of preparation and transparency of large samples, an investigation was made of the possibility of using a cell ½ × 1 × 6 in. By collimating the γ-ray source and directing the beam at various positions along the cell, it was found that the figure-of-merit did not vary more than

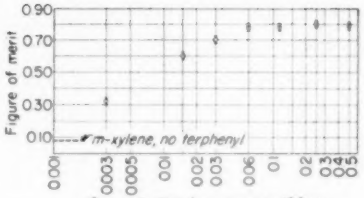

FIG. 2. Plot of effect of concentration of terphenyl in m-xylene

Liquid	*Figure-of-merit*
Benzene	0.07
Xylene	0.08
Naphthalene in benzene	0.15
Naphthalene + anthracene in benzene	0.36
Terphenyl in m-xylene 0.5 gm/100 cc	0.79
Terphenyl in benzene 0.5 gm/100 cc	0.76
Terphenyl in toluene 0.25 gm/100 cc	0.70
Terphenyl in cyclohexane (saturated)	0.58

±0.05 over the length of the cell. In these experiments no attempt was made to provide reflecting surfaces other than those present because of the pyrex container.

It is apparent that further extensive investigations of the properties of these solutions are possible and necessary, but it is already established that pulse heights equal to those of clear stilbene crystals can be obtained from clear solutions. Because large cells of clear solution are so simply prepared, it will now be possible to perform cosmic ray experiments previously made difficult because they require large, fast detectors.

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Radioactivity Air Filter Developed for AEC

A new inexpensive paper-like filter material designed for filtering fine radioactive particles from contaminated gaseous wastes has been developed for the Atomic Energy Commission by Arthur D. Little, Inc., Cambridge, Mass., research and engineering organization. The development may have general commercial or industrial use, for instance in filtering the smokestack gases which now cause fumes or smog.

The new material contains treated paper-making fibers in combination with very finely divided mineral asbestos fibers. The material is made in soft, flexible sheets which can be pleated and formed into shapes to fit filtering units of large capacity.

AEC facilities using cooling or ventilating air which might become contaminated with radioactive particles take extreme care to eliminate such particles before the air is discharged into the atmosphere. Air filters developed and used by the Chemical Warfare Service for protection against gas warfare have proved satisfactory, and for some years the Army has been supplying AEC with filter units. With the expansion of the atomic energy program, however, the demand for filters has grown rapidly. In order to develop alternate sources of supply and possibly to reduce filter costs, the AEC initiated a program for filter research and development.

The paper can be made on relatively slow Fourdrinier machines of a type found in a large number of paper mills fabricating soft saturating papers. Thus, the atomic energy program can be assured a diversified source of supply.

The filter units consist of deep, closely spaced pleats of filter paper fitted into wooden frames. The pleats are spaced and kept in line by deformed separators of ordinary paper which hold them in place and permit easy passage of the air to be filtered. The paper pleats and separators are anchored into wooden frames with plastic adhesives. The frames are in turn glued and screwed at all corner joints to produce a perfectly tight assembly. Gaskets of soft sponge rubber cemented around the edges of the frames prevent air leaks when the frames are clamped into place.

Properties of Scintillation Materials

Considerable work has been done recently in investigating various crystals for possible use in scintillation counters. At the meeting of the Metropolitan Section of the American Physical Society at Brookhaven on April 1, Robert Hofstadter of Princeton University presented data on the important crystals tested to date. These data (tables 1, 2) do not include only values obtained by Dr. Hofstadter, but also those of other investigators.

In Table 1, $\Delta K'$ has been used as a rough guide in searching for new materials. This is possible since the fluorescent yield of a material may be expected to be proportional to the effective number of π-electrons per gram of matter.

ΔK is a quantity equal to the difference in principal diagmagnetic susceptibility along the normal to the plane of the molecule and the average susceptibility in the plane of the molecule. $\Delta K'$ is $\Delta K/M$ where M is the molecular weight.

Many aromatic molecules have an anomalously high anisotropy (ΔK) in their principal diamagnetic susceptibilities, and the anisotropy is partially due to the large orbits of the π-electrons.

TABLE 1
Light Yield Properties of Aromatic Molecules

Material	*Color of crystal**	*Color of emitted light*	*Relative light yield for β-particles***	$\Delta K' \times 10^6$ *emu/gm*
Metal-free phthalocyanine	Deep blue	Unknown	Unknown	1.63
Pyrene	†	Blue	≥ 0.3	1.15
Anthracene		Blue	1.00	1.03
Chrysene	‡	Blue	≥ 0.6	0.99
Phenanthrene		Violet	0.3	0.94
Acenapthene		U. V.	0.1	0.92
Naphthalene		U. V.	0.25	0.89
Quaterphenyl††		Violet	≥ 0.6	0.84
β-Naphthol		Unknown	Unknown	0.79
Terphenyl	†	Violet	0.65	0.78
Diphenyl		Probably U. V.	0.15	0.77
Fluoranthene	‡	Blue-green	≥ 0.5	0.74
Stilbene		Violet	0.6	0.74
Benzene (solid)		Deep U. V.	Small	0.74
Fluorene	¶	Blue-violet	≥ 0.3	0.73
Tolane (diphenylacetylene)		Blue-violet	≥ 0.4	0.69
Dibenzyl		Violet and U. V.	0.6	0.64
Benzophenone		Unknown	Does not scintillate ≥ 0.1	0.60
Benzil	Pale yellow	Unknown	Does not scintillate ≥ 0.1	0.51
Catechol		Unknown	Does not scintillate ≥ 0.1	0.50
Durene††		Violet and U. V.	0.05	0.46
Hexamethyl benzene		Unknown	Does not scintillate ≥ 0.1	0.38
p-Benzoquinone	‡	Unknown	Does not scintillate ≥ 0.1	0.37
p-Dichlorbenzene		Unknown	Does not scintillate ≥ 0.1	0.31
Tetrachlorobenzene		Unknown	Does not scintillate ≥ 0.1	0.27
Hexachlorobenzene		Unknown	Does not scintillate ≥ 0.1	0.23
p-Dibromobenzene		Unknown	Does not scintillate ≥ 0.1	0.18
4-4′ Dibromodiphenyl		Unknown	Does not scintillate ≥ 0.1	0.05

* Except where noted, crystal is colorless.
† Crystal is colorless, but sample studied was yellow.
‡ Crystal is colorless, but sample studied was greenish yellow.
¶ Crystal is colorless, but sample studied was slightly brown.
** Integrated values, using anthracene as 1.0. Uncorrected for response of photomultiplier (5819).
†† New result, first reported here.

TABLE 2
General Properties of Crystals

Material	Emission spectrum A.U.	Absorption spectrum A.U.	Relative light yield‡ (uncorrected) for β particle	Decay constant¶ $\times 10^8$ sec^{-1}	Response to monoenergetic particles: Alpha	Beta	Proton	Light yield/Mev for different particles**	Density gm/cm^3	Melting point (°C)	Miscellaneous
Anthracene	4400 (60)*	Starts at ~ 4050	1.0	3.0 ± 0.5 (300°K) 1.2 ± 0.2 (77°K)	Nonlinear	Linear between 125–1900 kev	Nonlinear	$\frac{\beta}{p} \geq 2.0$ $\frac{\beta}{\alpha} \geq 8.0$	1.25	217	Good crystals rather hard to grow
Stilbene	4200 (weak) (360) 4080 (100) (strong)	Colorless	0.6	Between 0.6 and 1.2	...	...	...	Not constant	1.16	124	Good crystals readily obtained
Phenanthrene	4100 (100) 4300 (100)	Colorless	0.3	0.8	...	...	...	...	1.03	100	Extremely difficult to obtain clear crystals
Dibenzyl	3520 3710 3950 (weak)	Colorless	0.6	~ 1.6	...	...	...	...	1.00	52.5	Good crystals readily obtained
Terphenyl	3900 4050 4300	Colorless†	0.65	~ 1.2	...	...	...	$\frac{\beta}{\alpha} \geq 8.0$	1.23	213	Good crystals readily obtained; Rugged
Naphthalene	3450 (250)	Colorless	0.25	~ 6.0	...	...	...	Not constant	1.15	80	Good crystals readily obtained; Sublimes
NaI(Tl)	4100 (800)	Colorless 2930 2340	~ 2.0	25	Approx. linear	Linear	Linear	$\frac{\beta}{p} = 1.0$ $\frac{\beta}{\alpha} \geq 1.0$	3.67	651	Excellent crystals readily obtained; Hygroscopic
KI(Tl)	4100 (900)	Colorless 2870 2360	~ 0.5	> 100	Approx. linear	Linear	Linear	$\frac{\beta}{p} = 1.0$ $\frac{\beta}{\alpha} = 1.0$	3.13	582	Excellent crystals readily obtained
CsI(Tl)	White	Colorless	~ 1.5	> 100	...	...	...	...	4.50	621	Excellent crystals

CsI(Tl)	White	Colorless	~ 1.5	> 100	...	...	...	4.50	621	Excellent crystals readily obtained
LiI(Tl)	Blue Green	Colorless†	~ 1.0	> 100	...	...	...	4.06	446	Very hygroscopic
$CdWO_4$	5200	Yellow	~ 2.0?	Long	...	...	...	7.90	1325	Good small crystals readily obtained
$CaWO_4$	Green 4300	starts at 4500 Colorless	~ 1.0	Long	...	...	...	6.06	1535	
ZnS(Ag)	Blue Blue	starts at 4000	~ 2.0	> 1000 Decay not exponential	Approx. linear	...	$\frac{\beta}{\alpha} = 1.0$	4.10	1850	Only powder or small crystals obtainable

* Number in parentheses is the bandwidth at half-maximum.
† Sample studied was slightly yellow.
‡ This is the integrated light yield, with anthracene considered to be 1.0. Values are uncorrected for response of photomultiplier (5819).
** τ, the decay constant, is that which appears in $e^{-t/\tau}$.
** Values are correct in the range of alpha and proton pulses of 5 Mev.

"Tool Dolly" Goes Into Radioactive Areas

A one-armed robot on wheels, which can close doors, turn valves, take apart and reassemble complex machinery, and perform virtually every task the human hand can perform, has been developed by General Electric engineers for work in radioactive areas.

The device, known as a "tool dolly," is rolled into radioactive areas where men cannot go, and is operated by remote control from a shielded adjacent room. It moves under its own power along narrow-gage railroad tracks. Power and control are supplied through six cables which lead to the power source and control devices.

The tool dolly, developed for use on projects which GE is conducting for the Atomic Energy Commission, weighs approximately five tons, and resembles a railroad handcar with a small caliber deck gun mounted on it. The gun-like part of the apparatus is a telescoping arm, on the end of which are double clamps, similar to prosthetic hands. The arm can be extended or shortened, raised or lowered, by remote control. The "hand" itself is capable of a wrist-bending motion, rotation, and gripping.

There are six small electric motors in the arm and hand, and two dozen of them in the entire unit. In addition to the general purpose hand, the dolly is equipped with an hydraulically driven ram, electrically controlled, which can deliver a four-ton push; rotating devices for opening and closing valves; and several specialized attachments for taking apart or reassembling specific types of machinery.

A man operating the dolly must be able to see what the device is doing, and various methods for observing its movements from behind a shield can be used. To make observation easier, the dolly has been equipped with a three-foot mirror, which can be turned vertically

THE OMEGATRON, a recent development at the National Bureau of Standards in the realm of atomic instrumentation, is basically a miniature cyclotron. Developed by J. A. Hipple, H. Sommer, and H. A. Thomas, it can be used to determine the value of the nuclear magneton very precisely, so that the ratio of the mass of the electron to the mass of the proton will be known with greater precision than ever before. In addition to absolute measurements of mass, the omegatron has many other possible uses. Its high resolution and extreme sensitivity make it ideal for analysis of gases and vapors, and for the measurement of nuclear packing fractions. In operation, an electron beam parallel to a magnetic field ionizes atoms along its path. The ions are prevented from escaping axially by a d-c trapping potential applied to a sandwich array of guard rings. An r-f potential applied to both outer rings and guard plates produces an r-f field perpendicular to the magnetic field. When radio and cyclotron frequencies are the same for ions of a particular mass, the ions will spiral out to the collector.

or horizontally by remote control.

The valve-turning attachments are equipped with electric "feelers," which indicate to the operator whether or not the valve handle is properly centered in the grasp of the turner.

The controls are mounted in two boxes, about the size of small suitcases. There are 23 switches, nine of them for controlling the hand and arm. The control panels are also equipped with lights, which indicate the position of certain of the dolly's tools with respect to the apparatus being worked on. Six cables, each containing 25 different conductors, connect the controls to the dolly, it was explained.

Geological Survey Finds 3 New Uranium Minerals

Identification of three hitherto unknown uranium minerals has been announced by the Dept. of Interior.

They were found in a coating on gypsum on the 300-foot level of the Hillside Mine in Yavapai County, Arizona, together with schroeckingerite, another rare uranium mineral previously found only in Wyoming and Czechoslovakia. The new minerals have been named andersonite, swartzite and bayleyite by geochemists of the U. S. Geological Survey.

The minerals were first observed and collected by Dr. Charles A. Anderson, Survey geologist, in the Hillside Mine, a producer of gold, silver, lead, and zinc. The age of the metal mineralization is Cretaceous or early Tertiary, but the uranium minerals were formed recently.

Andersonite, swartzite and bayleyite are, respectively, hydrous uranyl carbonates of magnesium, of sodium and calcium, and of calcium and magnesium.

Uranium minerals were found in only one place, as a coating about $\frac{1}{16}$ inch thick on gypsum, in the oxidized zone,

and about 40 feet above the water level.

The source of the uranium is not known; it may be related to small aplitepegmatite dikes in the pre-Cambrian schist which are associated with the granite, or it may have been deposited with the ore-vein. In any case, the uranium carbonate minerals are clearly of secondary origin, and were deposited on the walls of the drift. Subsequent mining operations have completely obliterated the occurrence of the secondary uranium minerals.

In general, the several uranium minerals are intergrown with each other and with the gypsum and schist minerals. Only the schroeckingerite may be easily obtained in relatively large masses (about a pin-head in size) of a fair degree of purity.

BOOKS

Vacuum Equipment and Techniques (Div. I, Vol. 1, of National Nuclear Energy Series), edited by A. Guthrie and R. K. Wakerling, McGraw-Hill Book Co., Inc., New York, 1949, 264 + xvii pages, $2.50. *Reviewed by Earl W. Flosdorf, Director, Research and Development Division, F. J. Stokes Machine Company, Philadelphia, Pa.*

This is a record of the research work, done under the Manhattan Project and the Atomic Energy Commission, specifically concerned with the development and study of high-vacuum equipment by the personnel of the University of California Radiation Laboratory. The book compiles observations in the pioneering development of routine production of high vacuum in large systems on a scale never previously undertaken, *i.e.*, in the operation of the electromagnetic separation process. As such, it is a tribute to the unprecedented accomplishments of science, industry, government, labor and Army and Navy working as a team.

In presenting the fundamental considerations of vacuum practice involving parts of the kinetic theory of gases, it is assumed that the reader is already familiar with the theory but not necessarily with practice. Those parts of theory are presented without proof. Special equations of vacuum practice are developed in the book and discussed fully. Full references are given for all material of special interest in vacuum practice.

Equations are given for calculating molecular flow through pipes, including application of Knudsen's formula, circular pipes, thin slit-like tubes, equilaterally triangular ducts and ducts of other shapes, bends and elbows, as well as for calculating pumping speeds and for their measurement. The pumping speed of cold traps is discussed.

There is full discussion of the elements of a vacuum system, including the design and operation of rotary, oil-sealed, mechanical, vacuum pumps (backing pumps), various types of cold traps, booster and high-vacuum jet and diffusion pumps, high-vacuum valves and, finally, the construction of vacuum chambers and process tanks. A full chapter is devoted to vacuum materials and equipment with much detail given to welding, types of gaskets and grooves, flanges and valves. Extended discussion is given to means of producing motion within a vacuum chamber.

Another chapter is devoted to vacuum gages and the discussion includes new

types of McLeod gages and the various electrical gages which have been developed. There is satisfactory discussion of the limitations and applications of the various gages.

Relatively little attention has been devoted to the operational difficulties experienced with the large-scale vacuum installations in the Oak Ridge plant; this subject is being covered elsewhere in the series. There is, however, a full chapter devoted to leak-detection instruments and techniques. Some discussion is devoted to the theory of leak detection as well.

An appendix includes a summary of formulas useful in vacuum design, certain constants, conversion factors and physical properties. Also, there are lists of certain useful materials, oils, mechanical and diffusion pumps, and the nature and source of miscellaneous vacuum materials.

The book is recommended to those interested in the design and operation of high-vacuum systems.

Technion Yearbook, edited by Judah Wattenberg, American Technion Society, New York, 1949, 256 pages, $2.50.

Featured in volume 8 of this annual publication are 28 papers on topics pertaining to technical, industrial and educational progress in the United States and Israel. Of particular interest to readers of NUCLEONICS is the article, "Prospects in Industrial Application of Atomic Energy" by Philip Sporn, president of the American Gas and Electric Company and chairman of the Advisory Committee on Cooperation between the Electric Power Industry and the Atomic Energy Commission.

In this article, Mr. Sporn points out that the electric power industry has accepted the challenge of nuclear energy and is now in the midst of a five-year plan of expansion. And the competition between the two forms of power will depend, to a considerable extent, on how successful this expansion is.

After discussing estimates on a timetable for the availability of nuclear power put forth by the AEC's General Advisory Committee, Dr. Robert Bacher, former member of the AEC, and Dr. Enrico Fermi, Sporn predicts that there will be commercial generation of nuclear power in 10 to 15 years. It should be noted, however, that this statement was made before work on the Knolls power-producing reactor was postponed and also before work on the H-bomb was announced. As to when nuclear fuel would become a significant competitor of coal, it is predicted that this will take 15 to 25 years, or longer.

In answer to whether the electric power industry is waiting to see what happens with nuclear power, Sporn says, "Beginning in 1947 the industry started on a five-year $9 billion expansion program of its facilities, unprecedented in its history, or for that matter in the history of any other industry in this country. In the three-year period 1949–1951 alone, some 18,125,000 kw of new generating capacity will be completed and 15,045,000 of that—83%—is fuel-burning capacity, most of that coal. In working out that program, larger units, higher pressures, higher temperatures and new records for efficiency will be established. The possibility that nuclear reactors will become practical and economical devices has been reckoned with; but it has had no retarding effect on expansion plans based on the most modern technology possible today."—*J.D.L.*

BOOKS RECEIVED

Einführung in die Kernphysik (fourth, enlarged, edition), by Wolfgang Riezler, Hermann Hübener Verlag, Stader Strasse 84, Buxtehude, Germany, 1950,

309 pages, 8 plates, 1 pull-out chart, price DM 16.00 (bound in linen, DM 17.50).

Out of My Later Years, a collection of essays by Albert Einstein, Philosophical Library, New York, 1950, viii + 282 pages, $4.75.

Reflections of a Physicist, by P. W. Bridgman, Philosophical Library, New York, 1950, xii + 392 pages, $5.

Elementary Pile Theory, by Harry Soodak and Edward C. Campbell, John Wiley & Sons, Inc., New York, 1950, ix + 73 pages, $2.50.

Experimental Designs, by William G. Cochran and Gertrude M. Cox, John Wiley & Sons, Inc., New York, 1950, ix + 454 pages, $5.75.

The Nature of Physical Reality, by Henry Margenau, McGraw-Hill Book Co., Inc., New York, 1950, xiii + 479 pages, $6.50.

OTHER LITERATURE

The Geiger-Müller Counter, National Bureau of Standards Circular 490. In addition to the G-M counter itself, this booklet discusses methods of detecting counter pulses, applications of counters to quantitative measurements, proportional counters, and preparation and filling of G-M counters. Also, there are a number of examples of special forms of counters and a discussion of some of the electronic circuits commonly used to obtain an indication of counter response. A bibliography is included. *Available from Superintendent of Documents, U. S. Govt. Printing Office, Washington 25, D. C., 20 cents.*

On the Energy Loss by Fission Fragments Along Their Range, by N. O. Lassen, Ejnar Munksgaard, Copenhagen, 1949, 43 pages, Dan. kr. 4.00.

Chart of The Nuclides. This is a new edition of the "Chart of The Isotopes" prepared by the General Electric Research Laboratory and originally issued in 1948. A booklet entitled **"Nuclides and Isotopes"** and written by James Stokley contains supplementary information and accompanies the chart. *Both chart and booklet are available without cost from the General Electric Co., Dept. 6–221, Schenectady 5, N. Y.*

Radioisotopes—A Survey. This booklet was prepared by Kellex, a development and design engineering firm with seven years' atomic energy experience, which now provides research and consulting services in the industrial applications of radioisotopes. *Booklet available without cost from The Kellex Corporation, 233 Broadway, New York 7, N. Y.*

Proceedings of the First National Air Pollution Symposium. *Available from National Air Pollution Symposium, Executive Headquarters, 612 South Flower Street, Suite 332, Los Angeles 14, Calif., 148 pages, $2.50.*

Testing by The National Bureau of Standards, National Bureau of Standards Circular C483. Describes the Bureau's test policy, presents general information on testing, and lists fees for most of the test work that is done there. *Available from Superintendent of Documents, U. S. Govt. Printing Office, Washington 25, D. C., 25 cents.*

NUCLEONIC EVENTS

KNOLLS BREEDER HALTED; TO WORK ON SHIP REACTOR

Revision of the research program of the General-Electric-operated Knolls Atomic Power Laboratory, Schenectady, New York, to speed up design and development work on a land-based prototype for a ship propulsion reactor has been authorized by the Atomic Energy Commission. This change is also expected to provide for maximum participation of the laboratory technical staff in an expanded production program at the Hanford Works, Richland, Washington.

Named the ship intermediate reactor (SIR), this is a second and simultaneous attack by industrial contractors of the Commission on the problem of applying atomic energy to naval ship propulsion. The Argonne National Laboratory and the Westinghouse Electric Corporation are developing designs for a land-based prototype of a ship thermal reactor (STR) suitable for naval ship propulsion. Although both reactors will be designed to meet similar Navy performance specifications, they will be separate projects, involving different approaches and therefore different technical and engineering problems.

The reorientation of the KAPL research followed an AEC action that deferred the start of construction of the West Milton intermediate power-breeder reactor project, upon whose design the Knolls Atomic Power Laboratory has worked along with preliminary design of the ship reactor. It is estimated that from two thirds to three fourths of the research and development work already done on the intermediate power-breeder reactor will find use in the accelerated ship propulsion reactor project.

The plans for the SIR will call for a single-purpose machine designed specifically to produce large amounts of heat to be used for generating power. This is the difference between the SIR and the original West Milton power-breeder reactor. The latter was designed both for power production and for breeding reactor fuel.

GE ROTATIONAL TRAINING STARTS AT HANFORD

The first ten technical graduates reported last month at the Hanford Works, Washington, to begin the newly installed General Electric Company rotational training program, believed to be the first program of its kind at any US atomic energy plant.

Approximately fifty promising young technical graduates at a time ultimately will receive this training that will, for three months, offer them successive assignments in different parts of the vast plutonium manufacturing installation so that they can get acquainted with the plant's operation and the plant can get acquainted with their aptitudes.

AEC TO BUILD ACCELERATOR IN FRISCO BAY AREA

The Atomic Energy Commission has announced that a new classified research project is being undertaken in the San Francisco Bay area. The project involves the construction of a particle accelerator which will be used to pursue a classified research program for the

AEC. The project is expected to cost about $7,000,000.

The program will be undertaken by the California Research and Development Company in cooperation with the Radiation Laboratory of the University of California. The company is a subsidiary of the California Research Corporation which is owned by the Standard Oil Company of California.

The new project will be undertaken at the Livermore Naval Air Station through the cooperation of the Navy Department, which has agreed to work with the Commission in obtaining a transfer of the property. Work at the site is already under way.

AEC APPROVES 34 NEW LIFE-SCIENCE RESEARCHES

From November 1, 1949, through March 9, 1950, the Atomic Energy Commission approved 41 research proposals in the field of biology and medicine. Thirty-four of the proposals are for new research projects at universities, hospitals, and private research laboratories, six are for renewals of existing projects, and one covers a working agreement with the Fish and Wildlife Service of the Department of Interior.

Award of the new contracts, currently being negotiated by AEC Operations Offices, brings to 194 the number of AEC-supported research projects now being carried on in biology and medicine. Approximately $5,000,000 has been set aside for support of such research in non-AEC agencies during the current fiscal year.

U. OF MICHIGAN TO HAVE SUMMER ATOM SEMINAR

A pioneering course in "Public Policy and Atomic Energy" will be offered at the summer session of the University of Michigan, Ann Arbor, from June 26 to August 18. For graduate students and outstanding seniors, it will be one of the first courses in this field ever offered by a college or university. Marshall Dimock will conduct the course and government officials and private atomic experts will give some of the course lectures. Many of the talks will be open to the public.

Six major areas which will be considered in the proseminar: (*1*) legislative formation of policy; (*2*) administrative operation of the program; (*3*) coordination of military and civilian aspects of atomic energy policy; (*4*) governmental

ABOUT THE COVER

PRIMARY neutron standard—a 4-cm diameter beryllium sphere enclosing a gram of radium bromide, developed by the National Bureau of Standards—is calibrated in this tank of boric acid. Two indium and two manganese foils, which become radioactive under neutron bombardment, are used as detectors. They are suspended in the neutron-absorbing boric acid close to the standard, and then moved away at a predetermined, accurately known rate. Measurement of radiation from the foils, plus knowledge of their paths through the bath, permits accurate calculation of the total number of neutrons emitted by the standard. In the cover picture, one of the foils is shown being removed prior to being placed in a radiation counter. Photo from National Bureau of Standards.

relations with research institutions and business corporations; (5) community management of atomic energy sites; (6) international programs relating to atomic energy.

DEFENSE TEACHING LAUNCHED IN NATION-WIDE PROGRAM

The program known as the Civilian Radiological Defense Teachers Training Course recently got under way simultaneously at Oak Ridge, Los Angeles, and Upton, N. Y., with the completion of special five-week studies in radiological defense. The participants in these courses were selected by the Governors of their respective states, and it is expected that they will now supervise civilian defense training programs in their states as outlined by their Governors.

The courses, sponsored by the National Security and Resources Board through the General Services Administration, took place at the Oak Ridge National Laboratory, the University of California, and Brookhaven National Laboratory. The subjects covered were instrumentation, bomb phenomena, nuclear structure and reactions, radioactivity and fission products, medical effects of bomb radiation, and interaction of radiation with matter.

Also, at the University of Rochester School of Medicine and Dentistry recently, about thirty selected physicians from seven states took part in an intensive, week-long civilian defense course in which all phases of atomic injuries and treatment were covered. This course, and a similar one given at the same time at Johns Hopkins University School of Medicine, launched a nationwide project organized by the NSRB in cooperation with the Atomic Energy Commission.

Other courses will be given later at medical schools of the University of California at Los Angeles, the University of Alabama, Western Reserve University, and the University of Utah, and at the Argonne National Laboratory.

CAL TECH TO BUILD BILLION-VOLT ELECTRON SYNCHROTRON

The California Institute of Technology has just announced plans for a new high-energy-physics laboratory in which it will build a 1-Bev electron accelerator. The estimated cost of the completed installation, not including the laboratory building which is already available, is something over one million dollars. The Atomic Energy Commission will assist in financing the project.

The accelerator, an electron synchrotron, will be the most powerful machine of its type ever built. The construction of this machine will be speeded up by the fact that a magnet of the proper size is already in existence in the University of California's Radiation Laboratory where it was used for a pilot model of a 6-Bev proton accelerator. Because the latter machine, known as the bevatron, was designed to accelerate protons, which are 1,800 times heavier than the electrons to be used in the Cal Tech machine, some modifications of the magnet will be necessary. Dismantling and shipping of the magnet parts from Berkeley are already under way.

Plans call for building the electron synchrotron at Cal Tech in two stages. In the first stage, the bevatron model magnet will be used with only minor modifications and will produce electrons of 500-Mev energy. After some experience has been obtained at this energy, the additional modifications will

be made to bring it to the billion-volt level. Robert F. Bacher, chairman of Cal Tech's physics division, estimates that the first stage can be completed in approximately one year. An additional year and a half will be required to reach the billion-volt level. This means that on present schedules the billion-volt operation should be accomplished about the middle of 1952.

Annual operating costs of the experimental program to be undertaken after the billion-volt phase has been completed will be about $300,000 a year.

3-NATION CONFERENCE HELD ON RADIATION INSTRUMENTS

Representatives of the United Kingdom, United States and Canada recently attended a technical conference at the Canadian atomic energy establishment at Chalk River, Ontario, to discuss problems connected with radiation instruments.

Held within the Technical Cooperation Program as established among the respective governments, the conference, which was not open, dealt with detailed applications of instrumentation, particularly having to do with the reliability of electronic equipment used for radiation detection and measurement.

Representatives from ten atomic energy centers in the U. S. attended.

WORLD POWER CONFERENCE TO HEAR U.S. NUCLEAR PAPER

At the request of the organizing committee of the World Power Conference, a paper on atomic power production has been added to the list of 20 papers on various subjects that will be read at the power meetings in London, July 10–15. To be presented by Ward F. Davidson, Research Engineer, Consolidated Edison Company of New York, Inc., it is entitled "Nuclear Energy for Power Production—II."

NUCLEAR NEWSMAKERS

Robert F. Bacher, professor of physics and chairman of the Division of Physics, Mathematics, and Astronomy at the California Institute of Technology and former member of the Atomic Energy Commission, has been elected to the Board of Directors of the Consolidated Engineering Corporation.

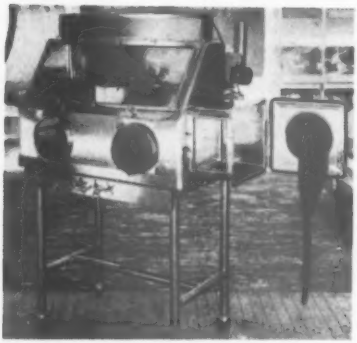
Darol K. Froman has been named technical associate director of the Los Alamos Scientific Laboratory to replace **John H. Manley,** who recently resigned the post to devote more time to the research currently being carried on at the laboratory.

The death of **Arthur J. Dempster** on March 11 has been announced by the Argonne National Laboratory where he

(Continued on page 87)

Maurice Goldhaber, professor of physics at the University of Illinois, has been appointed to the department of physics at Brookhaven National Laboratory to direct experimental and theoretical studies of the energy levels of atomic nuclei. His wife, Mrs. Gertrude Scharff-Goldhaber, a nuclear physicist too, has also accepted an appointment at Brookhaven. They will join the staff in June and collaborate on projects at the laboratory, where operating facilities will increase later this year with addition of a nuclear reactor (graphite-uranium pile) and a cosmotron (ultra-high-energy accelerator).

PRODUCTS and MATERIALS



LOW-INTENSITY DRY BOX

S. Blickman, Inc., Weehawken, N. J. Made of polished stainless steel, this 44 by 30 in. dry box has rounded, welded corners that make cleaning and decontamination easy. Two oval ports in the front of the box have rubber gauntlets sealed in, allowing access to the box without direct contact with radioactive materials. Electric outlets, hose cocks, and two fluorescent lamps inside the box are controlled from the outside. A slight negative pressure is maintained within the enclosure by an exhaust blower, and a low-pressure-drop filter in the air inlet allows an air flow of 10 ft^3/min. Safety glass is used for the front panel. An air lock is provided for insertion of materials. The unit is available with or without a stand.

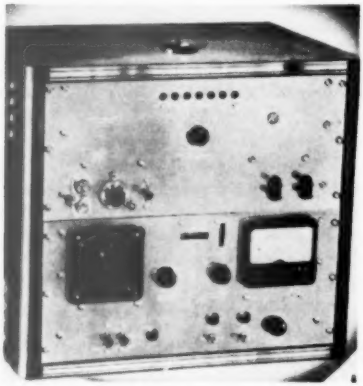
PROTECTIVE PAPER

Kimberly-Clark Corp., Neenah, Wis. Capable of absorbing up to 16 times its own weight of liquid within 30 seconds, Kimpak is finding increasing use in the nucleonics field as a covering for table tops and work surfaces. By absorbing spilled liquid, it lessens the danger of contamination. Advantages listed by the manufacturer are easy disposability, low cost, noncontaminating makeup, and ability to absorb dust and finely divided particles. Kimpak is available with a wide variety of embossings in thicknesses ranging from 0.01 to 0.55 in. Many different backing papers are also available. Recommended by the manufacturer for use in the radioactivity field is the whipcord-embossed type 201 Kimpak, 0.03 in. thick, with a 40 lb Cromwell water-resistant backing paper glued to its under side. This particular Kimpak weighs 35.1 lb/1,000 ft^2, including the 14.7 lb weight of the backing. It is available in 800-ft rolls in any width between 2 and 40 in., and in sheets with widths in the same range and lengths from 10 to 110 in. Minimum order is 1,000 ft^2. Also available is a nonabsorbent Kimpak, type 500, which is brown instead of white. Both types are antitoxic.

HIGH-SPEED RECORDER

Potter Instrument Co., Inc., 115 Cutter Mill Rd., Great Neck, L. I. Designed for use with Potter electronic counters and counter chronographs, a

new high-speed Teledeltos paper recorder uses 24 styli for recording a six-digit number. A 1-2-4-8 decimal designation is used for each digit. Count or time interval registered by the counter is transferred to Teledeltos paper at the completion of each measurement. The counter is then automatically reset.



ALL-PURPOSE SCALER

Nuclear Instrument & Chemical Corp., 223 W. Erie St., Chicago 10, Ill. Geiger, proportional or scintillation counting can be done by either automatic or manual methods with the new Ultrascaler. Two inputs are provided —one for Geiger pulses and the other for very small proportional pulses requiring linear amplification. A resolution time of 2 μsec is claimed for the Higinbotham-type scale-of-128; scale selection is provided to permit use of smaller scaling factors. A built-in register indicates total number of counts, and a built-in timer can be set for counting over a predetermined time. The timer also indicates elapsed time when the instrument is set for a predetermined count. Stabilized high voltage is variable to 2,500 volts, and a time delay relay prevents over-voltage surge on the Geiger tube when first turned on.

PORTABLE SCALER

Berkeley Scientific Co., Richmond, Calif. Battery operation makes the model 80 portable G-M scaler independent of a-c power supply. The instrument consists of a G-M tube and probe, an electronic scale-of-eight, a mechanical register, and a high-voltage supply which is adjustable from 900 to 1,102 volts in ten steps. A maximum continuous counting rate of 14,400 cpm is claimed, and pulse resolution time is said to be 90 μsec. Summation of counts is indicated by the mechanical register; a microammeter is used for interpolation. Housed in a hermetically sealed one-piece magnesium casting with removable backplate, the instrument measures 12¾ in. by 9½ in. by 7¼ in. and weighs 15 lbs.

DISPERSED PLASTICS

Chemical Manufacturing Division, M. W. Kellog Co., P. O. Box 469, Jersey City 3, N. J. The first two of a series of Kel-F (trifluorochloroethylene polymer) dispersions are now available. These dispersions make the plastics available in a form that permits their application to materials and equipment not amenable to processing by conventional plastic molding. Type N-I is a nonaqueous dispersion containing approximately 20% of dispersed Kel-F plastic. Nonaqueous type NW-25 con-

tains 27 % total dispersed solids. Both may be applied by spray, brush, or dip methods. Fusion of the dispersed film is accomplished by heating at temperatures ranging from 225 to 360° C.

RISE-TIME INDICATOR

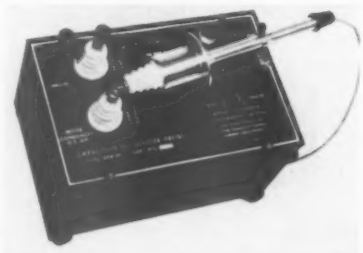
Electronic Systems Co., 555 E. Tremont Ave., New York 57, N. Y. The model 632-B pulse rise-time indicator is an instrument for the accurate plotting of the rise time of rapidly rising positive voltage pulses. Rise times from 0.005 to 0.1 μsec can be read in 20 steps. A delay line of variable length is adjusted until the vacuum tube voltmeter in the instrument reads a maximum; the calibrated line is then a measure of rise time and may be used to plot the leading edge. Positive peak pulses from 1 to 200 volts may be calibrated with a maximum error of ± 0.005 μsec. Operating from 110 volts, 60-cycle, the instrument uses 60 watts. Weight is less than 25 lbs.

MINIATURE POWER SUPPLY

Eltron, Inc., Jackson, Mich. Operating from a 3-volt dry or wet cell, the model 103D-6 delivers a regulated and filtered 900-volt d-c output for G-M counters. The unit measures 1⅝ in. by 2 5/16 in. by 2¾ in. and weighs 12 ounces. Output voltage is constant within one percent for an input battery voltage varying from 2.2 to 3.5 volts. Output ripple is less than 0.2 volts. Available for either fixed or plug-in mounting, the unit is said to have a life of more than 1,000 hours. Other units using the same four-pole vibrator in a patented self-rectifying voltage multiplier circuit deliver power outputs ranging from milliwatts to about three watts at output voltages as high as 2,500 volts.

D-C MILLIVOLTMETER

Industrial Control Co., 1462 Undercliff Ave., New York 52, N. Y. Characterized by an extremely low internal residual, high input impedance, and gain stability comparable to that obtained in a-c vacuum-tube voltmeters, the model 200-A millivoltmeter can detect d-c voltages as low as 5 μvolts, or, currents to a level of 10^{-11} amp with suitable shunts. Output from the instrument is an a-c voltage whose rms magnitude is said to be precisely 1,000 times that of the d-c input. Operated from a 115-volt a-c line, the millivoltmeter can be used to make any a-c vacuum-tube voltmeter direct reading for d-c millivolts or d-c μvolts. It can also be used as an amplifier in servomechanisms.



D-C CAPACITIVE DIVIDER

Millivac Instruments, P. O. Box 3027, New Haven, Conn. The PR6-NL 1,000-to-1 capacitive d-c divider is an

ultrasensitive measuring device designed for use with the model MV-17b d-c millivoltmeter. Currents to be measured are fed into a 500 $\mu\mu$f capacitor for a definite period of time. A switch then transfers the accumulated charge to an 0.5 μf capacitor which supplies d-c power to the millivoltmeter. Current measurements down to 5×10^{-13} amp are said to be possible with a charging time of 50 sec. The PR6-NL can also be used for infinite-impedance voltage measurements between 1 volt and 30 kv.

RARE GASES

Linde Air Products Co., 30 E. 42nd St., New York 17, N. Y. Krypton, xenon, and argon gases for laboratory use are available in liter bulbs as well as in small rare-gas cylinders. Both krypton and xenon are being produced in large quantity at the company's Essington, Pa., plant.

THERMOSETTING RESIN

Electro Chemical Supply & Engineering Co., 750 Broad St., Emmaus, Pa. Self-hardening at room temperature, Duron is a new thermosetting resin which will adhere to concrete or metal without the use of a primer. Developed for use in cements for joining brick and tile, for coating concrete, steel, or wood, and for impregnating wood, the new resin is said to be inert to solvents, fats, oils, greases, and alkalis of all concentrations. It is also resistant to a wide range of acids.

HIGH-VOLTAGE SUPPLY

Dale Pollack, 352 Pequot Ave., New London, Conn. The model 4 power supply operates from a battery input of 3.0 volts and provides an output of 1,000 volts. With a volume of 12¼ cubic inches, it weighs 15 ounces. Battery life of 65 hours is claimed.

LITERATURE AVAILABLE

Catalog B. Describes nucleonic instruments, radioactive reference sources, laboratory equipment, lead shields, tagged chemicals, and film badge service available. *Tracerlab, Inc.*, 130 *High St., Boston* 10, *Mass.*

Catalog K. Nucleonic instruments and accessories are described. *Nuclear Instrument & Chemical Corp.*, 223 *W. Erie St., Chicago* 10, *Ill.*

Catalog D-185. Monocular and binocular laboratory microscopes are described. *Bausch & Lomb Optical Co., Rochester* 2, *N. Y.*

Chart 501. Mechanical and electrical properties of AlSiMag ceramics are tabulated and depicted graphically in this four-page folder. *American Lava Corp., Chattanooga* 5, *Tenn.*

Bulletin 112. Work forms, graphs, tables, and drawings needed for design of air-conditioning installments using the controlled-humidity process are included in this book. Equipment is detailed. Price is $2.50. *Niagara Blower Co.*, 405 *Lexington Ave., New York* 17, *N. Y.*

Bulletin 1025. Utiliscope wired television systems are described. Possible applications are detailed. *Diamond Power Specialty Corp., Lancaster, Ohio.*

Kelefax. Bimonthly publication will contain short articles, reference data, and information about Keleket instruments used in nuclear science. *Kelley-Koett Instrument Division*, 42 *E. Sixth St., Covington, Ky.*

Catalogs 94 and 95. Glass pipe and fittings, including a new metal-to-glass and glass-to-glass coupling, are described in catalog 94. Precision-bore round, square, and capillary tubing for use in barometers, manometers, burettes, and other precision instruments is described in catalog 95. *Glass Division, Fischer & Porter Co., Hatboro, Pa.*

REFLECTIONS

NOTE: *In connection with the article "Education for Nuclear Engineering" which appeared in NUCLEONICS in July, 1949, and which proposed the idea of making nuclear specialists out of engineers, it was pointed out that Reed College had taken a parallel step in offering a course designed to make nuclear specialists out of doctors.*

In response to an invitation from the Editor, Lt. Col. Clinton Maupin of the Marine Corps, a student in the first course given at Reed, has sent us for publication his recollection of the course itself and comments on its merits:

DEAR SIR:

In September of 1948, three medical officers of the United States Army Medical Department were ordered to report to Reed College, Portland, Oregon to pursue a six months' course of instruction in Medical Aspects of Radiation Hazards.

Certain members of the staff of Reed College's Division of Mathematics and Natural Science had taken on the nuclear training program as a joint operation. Since the program had originally been proposed by the AEC several months before but no definite agreement had been reached on the detailed scope of the course, the staff was faced with the problem of crystallizing general ideas into specific courses, assigning instructors, and working the program into the general schedule of the college. Furthermore, advice that the program was going into actual operation with definite assignment of students to the school was not received until less than a week prior to starting of classes.

At interviews by the faculty members with the officers, it became apparent that there was a large gap to be bridged between the practice of medicine and nuclear physics, radiochemistry and radiobiology. This applied particularly to mathematics and physics. (Most medical schools require no more than college algebra and introductory college physics, the details of which because of "atrophy of disuse" become vague.)

Even in our group of three, backgrounds were quite diverse. One officer had practically no mathematical background, but was an expert roentgenologist; another was familiar generally with calculus, but had only the minimum experience in roentgenology.

It was decided to organize a class in general mathematics, a review of general college physics, and lectures in organic and physical chemistry courses, before going into nuclear physics and the radiochemical laboratory.

In view of our mathematical backgrounds, the review in physics was presented in a relatively nonmathematical manner. Emphasis was placed on the proper handling of units and methods of choosing formulas. This course, as well as the subsequent one in nuclear physics, was closely coordinated with the concurrent basic mathematics course.

The basic mathematics course began with a review of algebra and an introduction to fundamental trigonometry and calculus. The latter covered practice in differentiation and integration of commonly encountered functions, and applications to rate of change and maxima and minima problems. Emphasis was placed on logarithms, laws of variation and probability, and statistics, and their practical use was stressed with a minimum of formula development and theoretical considerations being employed. The text used was "Introduction to Mathematical Analysis" by F. L. Griffin (Houghton Mifflin Co., Boston, Mass.); this book was an admirable one for the purpose since it is confined to the essentials and has abundant problems of practical type.

Auditing of organic and physical chemistry courses served to refresh rusty memories in chemical terminol-

ogy. (It was felt that a general chemical review course analogous to the basic mathematics course would have better fitted our needs, and such a course, I understand, was established beginning with the next class.)

Having thus been indoctrinated basically, we began the two feature courses, nuclear physics and radiochemistry, which got underway on November 9 and December 1, respectively. In both courses, "Nuclear Radiation Physics" by R. E. Lapp and H. L. Andrews (Prentice-Hall, Inc., New York) was the bible. Here again utilization was the theme, with the result that essentials were emphasized, development of equations kept at a minimum, and technical matters such as electronic circuits, details of the pile, binding energy equations, *etc.*, were covered only for the purpose of general information. Subjects particularly applicable to the physician, such as health physics, were, of course, discussed in detail.

In the laboratory, experimental work centered around proficiency in the use of radiation detection instruments, their application to chemical procedures, and the special techniques for dealing with radioactive materials.

In one phase of this work, we physicians found ourselves more or less at home. This was in the modified sterile technique required in handling radioactive materials. The experiments were graduated from the simple to the complex. They ranged from determining the characteristic voltage plateau curve of a Geiger tube and proving the inverse square law of radiation intensity to demonstrating coprecipitation and inoculating animals with radioiodine to show major absorption of that element by the thyroid gland. This course was well planned and presented in a practical manner; it gave us a good insight into the applicability of radioisotopes to chemistry, biology, and medicine and to their limitations and hazards.

During the last four months of the training program, biology and biochemistry courses which pointed up radiation aspects ran concurrently with the physics lecture course and the radiochemistry laboratory work. Emphasis was placed upon genetics and the effect of ionizing radiations on chemical, biological and heredity processes.

In summary, the course given at Reed College was designed to introduce us to the medical aspects of radiation hazards and prepare us for a six months' tour of on-the-job training at an AEC installation. It is my opinion that it succeeded in this.

As in all original projects, some redundancies crop up, and some deficiencies occur. These, however, were few, and nonessentials have been eliminated and deficiencies corrected for subsequent courses. It is in this type of course that the physician can obtain a most excellent background in nuclear radiation without being asphyxiated with mathematical, physical, and chemical intricacies.

CLINTON S. MAUPIN, Lt. Col., MC, USA
Army Industrial Hygiene Laboratory
Army Chemical Center, Maryland

Nuclear Newsmakers *(Cont. from p. 81)*

served as director of the Division of Mass Spectroscopy.

Francis B. Silsbee, chief of the Electricity and Optics Division of the National Bureau of Standards, has been elected president of the Washington Academy of Sciences.

Patrick M. Hurley has recently assumed the position of executive officer of the Department of Geology at the Massachusetts Institute of Technology. On the MIT staff since 1938, he has lately been engaged in research on the applications of nuclear science to geology for the Office of Naval Research.

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RADIATION RESEARCH

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